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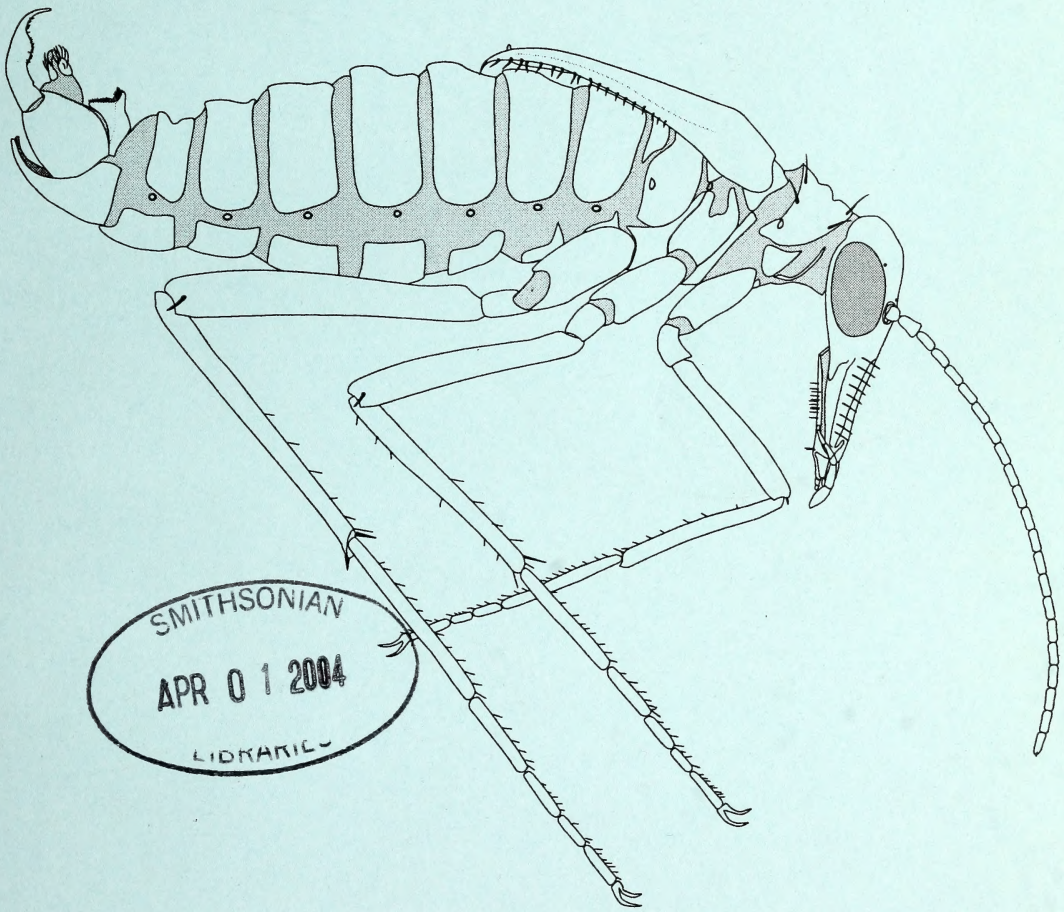

ESBC

***COVER*:** Lateral view of a male snow scorpionfly, *Boreus insulanus* Blades (Mecoptera: Boriedae). Adults of this species, like others in the family, are about 4 mm in length, flightless, and are active during the winter months. At present, *Boreus insulanus* is known only from 3 locations on southern Vancouver Island, suggesting that it may be an endemic species.

Boreus species are found primarily in mountainous terrain, between 200 m and 2000 m elevation, throughout the Holarctic. In North America, the greatest diversity of species is in the region from Oregon to Alaska and east to the Rocky Mountains.

Original line drawing by David Blades, published in the species description in Volume 99 of the JESBC (2002).

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A positive correlation between photoperiod and development rate in summer species of Odonata could help to make emergence date appropriate to latitude: a testable hypothesis[1]

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ABSTRACT

In the western Nearctic and the Palaearctic Regions several species of Odonata occur, without evident gaps in distribution, from latitude 50° N northwards to the Arctic Circle (66°30'N) and beyond. The decline in incident solar radiation along this latitude gradient does not appear to be reflected, as might be expected, in progressively later emergence, despite the progress of metamorphosis being dependent on ambient temperature. On the contrary, reports indicate that, in some species, northernmost populations may emerge at least as early as, and sometimes even earlier than, more southerly populations, suggesting that some mechanism exists that enables larval developmental rate to compensate for latitude. Reported responses by late-stadium larvae to photoperiod, placed in the context of seasonal changes of photoperiod at different latitudes, make it plausible to postulate the existence of a single, fixed response to photoperiod that would continuously adjust developmental rate to latitude, at least between 50° and 70° N. In Odonata such a response, to be effective, would be confined to species possessing a Type-2 or Type-3 life cycle, in which more than one stadium precedes metamorphosis in spring or early summer. The hypothesis proposed here does not invoke genetic heterogeneity of response in populations at different latitudes, such as has been detected in certain other insects. The response predicted by the hypothesis may complement, rather than substitute for, other mechanisms of seasonal regulation. Steps are described by which the hypothesis could be tested in Odonata.

INTRODUCTION

Western Canada is of interest to odonatologists because it includes the highest latitudes at which Odonata maintain populations in the Nearctic Region and because it is where many species, commoner and better known in the United States, reach the northernmost limits of their distribution. Some species in western Canada maintain a virtually continuous distribution from about 50° to 70° N, i.e. from southern British Columbia (BC) to the Yukon and Alaska. Reports by Cannings *et al.* (1991), Cannings and Cannings (1997) and Cannings (2002) have done much to characterize this distribution and have provided a major impetus for this paper.

The tree line generally forms the latitudinal limit to the occurrence of resident populations of Odonata: no species of Odonata breeds on the Arctic slope of Alaska (Cannings *et al.* 1991). In Canada the tree line occurs at progressively lower latitudes towards the east, reaching its southernmost limit close to Churchill, Manitoba, at about 58°46' N. This means that the 88 species of Odonata that occur in both British Columbia

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[1] Text based on an invited, oral contribution to the Workshop "North American Dragonflies", included in the Joint Meeting of the Entomological Society of Canada and the Entomological Society of Manitoba, Winnipeg, Manitoba, 9 October 2002.

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(BC) and the Yukon (Cannings 2002) exist as breeding populations over a wider range of northerly latitudes than anywhere else in the Nearctic Region. Therefore I focus here on the Odonata of western Canada, mainly northern BC and the Yukon.

Another impetus for this paper has been the clarifying research by Norling on the seasonal regulation of those Odonata that have a wide latitudinal range in Sweden (Norling 1976, 1984a, b, c). As Norling (1984b) has remarked, species occurring over such a wide range of latitude will be exposed to a south-north gradient characterized by progressively shorter (and usually cooler) summers, by longer (and usually more severe) winters, and by less predictable weather in summer. They will also experience progressively longer photoperiods between the spring equinox and the summer solstice (i.e. the time of most active pre-emergence development). Such exposure implies an extreme commitment in the northernmost species of these Odonata to early emergence, because inclement weather during the brief northern summer can seriously erode the time available for imaginal maturation and reproduction.

Noting the seasonal placement of the flying season of odonates along this climatic gradient has led me to postulate a hypothetical mechanism whereby the retarding effects of the climatic gradient might be compensated for by a unitary response to photoperiod. In the rest of this report I explain the reasoning leading to the hypothesis and its implications: first, I review what is known about seasonal regulation of Odonata, thus providing the information base with which the hypothesis must be consistent; second, I formulate the hypothesis and explore its implications for several variables; and third, I present a protocol for testing it.

The full scientific names of all species mentioned in this account, if not in the running text, are given in Table 1.

SEASONAL REGULATION OF ODONATA: THE BACKGROUND

Norling (1984b) and Pritchard (1982) have placed the topic of seasonal regulation in Odonata in broad ecological perspective. The question of seasonal adjustment according to latitude is a subset of the more fundamental one of how a group of tropical origin such as the Odonata has successfully colonized temperate latitudes. Pritchard (1982) concluded that the Odonata, unlike other aquatic insect orders such as the Ephemeroptera and Plecoptera, remain warm-adapted and have retained cold-intolerant early larval and adult stages; so they have evolved a larval diapause that restricts the cold-intolerant stages to the warmer times of year. This interpretation has been supported by results obtained for several species (Norling 1984b) so that diapause in the egg and/or larva can be regarded as a hallmark of the Odonata (among aquatic insects) that have colonised high latitudes.

Three main Types of odonate life cycle (described below) are encountered in temperate latitudes (Corbet 1960). The first two Types, originally classified as 'spring' and 'summer' species',respectively, have been defined by Corbet and Corbet (1958) and by Corbet (1999). Paulson and Jenner (1971) observed that this dichotomy applies to life cycles in high, but not necessarily low, temperate latitudes. The third Type, a subset of summer species, comprises species that are obligatorily univoltine (completing one generation per year). These Types refer to life cycles, not species. For example, within one population of *Anax imperator* Leach a single population can exhibit two Types of life cycle (Corbet 1957a); and populations of *Coenagrion hastulatum* (Charpentier) at different latitudes can do likewise. For example, in southern Sweden at 58°42' N, this species is mainly univoltine with a Type-2 life cycle, overwintering mainly in the penultimate larval stadium, (Norling 1984c) whereas in northern Sweden at 63°50' (Johansson and Norling 1994) and 67°50' N (Norling 1984c) it is mainly semivoltine

Table 1

Relative positions of flying seasons of Odonata that occur from southern BC north to the tree line (source: Cannings 2002).

Species	A	B	C	D
Zygoptera				
Coenagrion interrogatum (Hagen in Selys) (2)		x	x	
C. resolutum (Hagen in Selys) (2)		x	x	
Lestes dryas Kirby (3)	x			
L. disjunctus Selys (3)	x			
Enallagma boreale (Selys) (2)	x			
E. cyathigerum Charpentier (2)	x			
Anisoptera				
Aeshna canadensis Walker (2)	x			
A. eremita Scudder (2) *	x			
A. interrupta Walker (2)	x			
A. juncea (Linnaeus) (2)	x			
A. septentrionalis Burmeister (2)				x
A. sitchensis Hagen (2)		x	x	
A. subarctica Walker (2)	x			
Cordulia shurtleffi Scudder (1)	x			
Leucorrhinia borealis Hagen (1)	x			
L. hudsonica (Selys)(1)	x			
L. patricia Walker (1)		x		
L. proxima Calvert (1)	x			
Libellula quadrimaculata Linn. (1)	x			
Somatochlora albicincta (Burmeister) (1)		x	x	
S. franklini (Selys) (1)		x**	x**	
S. hudsonica (Hagen)(1)		x	x	
S. kennedyi Walker (1)		x		
S. minor Calvert (1)	x			
S. semicircularis (Selys) (1)	x			
S. septentrionalis (Hagen) (1)		x		
Sympetrum danae (Sulzer) (3)	x			
S. internum Montgomery (3)	x			
S. madidum (Hagen) (3)	x			
Total species	19	9	6	1

Key to columns:

A Flying season begins earlier in south and ends later in north.

B Flying season begins at same time in south and north.

C Flying season begins at same time in north and south but ends later in south.

D Flying season begins later in south and ends at same time in north and south.

Note: The number in parentheses after each species denotes its probable, typical life-cycle Type (see text). Where pertinent data for North America are lacking (e.g. in *Somatochlora* spp.) the life-cycle Type for the genus has been inferred from Palaearctic congeners.

*The only evidence available (Walker 1958) indicates that *A.eremita* can enter diapause in F-0, a characteristic of the T1 life cycle.

**Unlike Cannings (2002), Walker and Corbet (1978) state that the flying season of *S. franklini* is *later* in the north.

(completing a generation in two years), or even partivoltine (completing a generation in more than two years), with a Type-1 life cycle. A further example of such latitude-dependent variation is *Aeshna juncea* (Linnaeus), which exhibits a Type-2 life cycle in southern Sweden but a Type-1 life cycle in northern Sweden (Norling 1984b). *Aeshna viridis* Eversmann, in contrast, apparently always retains a Type-2 life cycle because its long-day larval diapause prevents larvae from entering the final stadium (F-0) in late summer (Norling 1971). The expression 'T1 species' will be used here as a shorthand for 'species exhibiting a predominantly Type-1 life cycle' and the corresponding abbreviations will be used for the Type-2 and Type-3 life cycles.

The T1 life cycle, typified by spring species

By spending the last winter before emergence in F-0, such species can respond promptly and synchronously to rising temperature in spring; thus they tend to emerge early. Their eggs typically develop directly, hatching about one month or less after being laid, although those of some Palaearctic *Somatochlora* are facultative in this respect, developing directly if laid early in the summer but entering diapause if laid later (Sternberg 1995). Eggs of *S. franklini*, sometimes at least, enter diapause (Walker 1925). Probable T1 examples in Canada are species of *Leucorrhinia* and *Somatochlora*, which, by analogy with their Palaearctic congeners, are semi- or parti-voltine, having life cycles lasting more than one year. *Leucorrhinia intacta* (Hagen) is known to have this Type of life cycle in southern Ontario (Deacon 1975).

The T2 life cycle, typified by summer species

Because they spend the last winter in one or more late stadia preceding F-0, such species typically emerge later than T1 species and with less synchronization (Corbet and Corbet 1958). Likely examples in Canada are species of *Coenagrion*, *Enallagma* and *Aeshna* which, by analogy with their Palaearctic congeners, are probably uni-, semi-, or parti-voltine. The eggs of *Aeshna* species typically overwinter in diapause (for North American species see Lincoln [1940] and Halverson [1984]). Those of *Coenagrion* and *Enallagma* typically develop directly (for Canadian species of *Coenagrion* see Sawchyn [1971] and Baker and Clifford [1981]; and for species of *Enallagma* see Pilon and Masseau [1984]). Despite commencing growth in their last spring in more than one stadium, T2 species can improve their synchronization of emergence by using a system of rising lower temperature thresholds that enable retarded larvae to catch up with more advanced ones (Corbet 1957b; Lutz 1968).

The T3 life cycle, typified by obligatorily univoltine species

These species represent a subset of T2. They typically, but not necessarily (see Corbet 1956a, 1999), overwinter as eggs in diapause. Larval development is completed in two or three months in spring and early summer, and adults die in late summer. Examples from Canada are species of *Lestes* (Sawchyn and Church 1973; Sawchyn and Gillott 1974; Laplante 1975; Baker and Clifford 1981) and from North America species of *Sympetrum* (Krull 1929; Tai 1967; Boehms 1971; Peterson 1975). These observations conform with results for Palaearctic species of these genera (Corbet 1999). In several species of Palaearctic *Sympetrum* and in at least one species from North America, egg diapause is facultative (Tai 1967; Corbet 1999). Like T2 species, T3 species also, theoretically, have available the use of rising temperature thresholds to reduce temporal variation in spring before emergence. From experiments conducted by Krishnaraj and Pritchard (1995) on *Coenagrion resolutum* and *Lestes disjunctus*, it is reasonable to assume that larvae of T2 and T3 species differ in their temperature coefficients for growth, the latter having the higher coefficient as well as having a higher attack coefficient and a more flexible foraging mode.

Some T1 and T2 species, and most T3 species, have evolved cold-resistant (i.e. diapause) eggs. In all such species, however, a relatively high temperature threshold for

hatching after completion of diapause development ensures that the earliest larval stadia are not exposed to low temperature in spring (for T3 species see Sawchyn and Gillott 1974; Boehms 1971; Tai 1967).

The amount of development to be completed in spring before emergence constitutes a major difference between T1 species and the rest. T1 larvae, resuming development in spring, especially at the highest latitudes, are ready to respond almost immediately to rising temperature by initiating metamorphosis, in contrast to those of T2 and T3 which still have one or more larval ecdyses to undergo before metamorphosis can begin. This disparity alone could enable T1 species to emerge earlier at higher latitudes.

Two Episodes in the seasonal regulation of Odonata can be distinguished (Norling 1976, 1984a, b, c). These represent the manifestion of two discrete strategies that can both act, though at different seasons, to ensure that emergence is positioned at an appropriate time of year.

Episode 1. Retardation of larval development in late summer and early autumn so that the larval population overwinters in an appropriate, cold-resistant stage. This process is usually accomplished by the onset of a diapause induced by photoperiod. Initially long (e.g. mid-summer), and perhaps sometimes decreasing, photoperiods (Norling 1984b) postpone entry to one or more late stadia, whereupon short photoperiods prevent development from proceeding further before the onset of winter. This Episode concerns *pre*-diapause development and is well developed in the T1 life cycle in which diapause is induced in F-0; it determines the stadium and/or intrastadial stage in which the last winter will be passed.

Episode 2. The placement of emergence, in spring and early summer, early in the season favourable for adult activity and survival. This Episode concerns *post*-diapause development. It is achieved by responses quite different from those occurring during pre-diapause development. In this Episode, instead of being retarded (as in Episode 1), larval development is *accelerated* under long photoperiods (Norling 1984b). The larval response to photoperiod characteristic of Episode 1 has evidently been reversed among larvae that have experienced a period of low (winter) temperature and/or decreasing (or short) photoperiods.

Norling (1976, 1984a, 1984b) investigated the responses of odonate larvae to photoperiod in populations at different latitudes between 58°42' and 68°20' N in Sweden. Photoperiod influences seasonal regulation in *Leucorrhinia dubia* (Vander Linden) (a T1 species studied by Norling) in late summer (Episode 1), when long photoperiods delay entry to F-0 and then short photoperiods prevent any F-0 larva from initiating metamorphosis. Norling (1976) distinguished five phases of morphological development within F-0, a stadium that had hitherto been regarded as a homogeneous developmental stage. The photoperiodic response of each intrastadial phase differs, ensuring that larvae entering spring in F-0 are in phase 4 which, unlike the phases preceding it, is characterized by larvae being able to respond promptly to increasing photoperiods, by accelerating development. The last intrastadial phase (phase 5) is brief, responsive to temperature, and unaffected by photoperiod. This set of responses results in emergence of *Leucorrhinia dubia* occurring some 7-10 days earlier than if all larvae were to remain static within F-0 and thus fail to reach phase 4 before the onset of spring.

The seasonal progression of photoperiod across the latitudinal range covered by Norling's work changes greatly according to latitude (Fig. 1). Norling (1984a) found that the critical photoperiods inducing diapause in summer (Episode 1) or accelerated development in spring (Episode 2) differed in larval populations at the extremities of this latitudinal range. Such a phenomenon, in which discrete populations at different latitudes differ genetically in their response to a given photoperiod, was already known from the work by Danilevskii and his associates on Lepidoptera between 40° and 60° N in

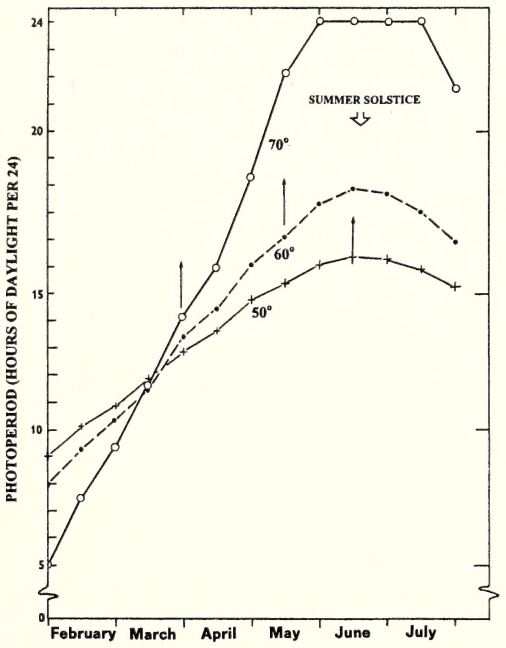

Figure 1. Progression of photoperiod (defined as the interval between sunrise and sunset) at three latitudes during spring and early summer. Vertical arrows show the extent to which the photoperiod on the date indicated is lengthened by inclusion of morning and evening Civil Twilights. (Data from Beck 1968.)

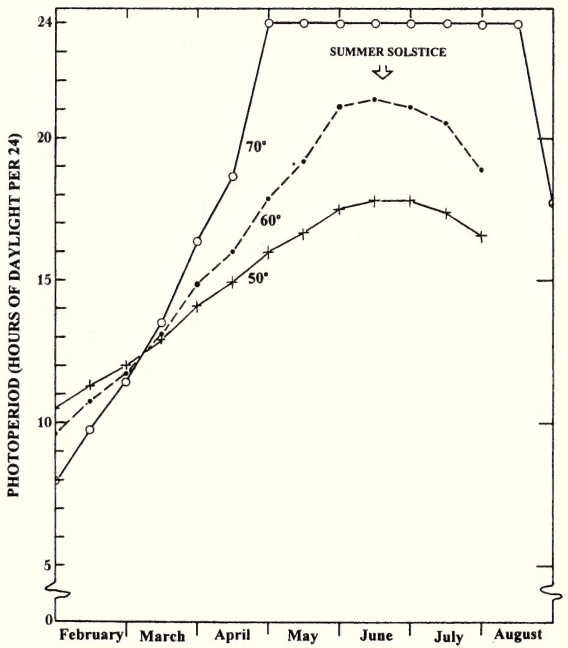

Figure 2. Progression of photoperiod (defined as in Fig. 1 but with the addition of the Civil Twilights at sunrise and sunset) at three latitudes during spring and early summer. (Data from Beck 1968.)

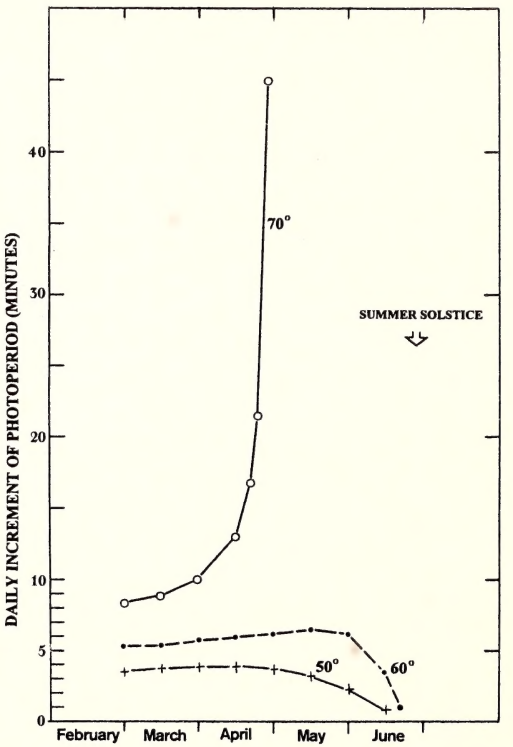

Figure 3. The daily increment of photoperiod (defined as in Fig. 2) at three latitudes during spring and early summer. (Data computed from Wood and Jaramillo (2002) by Dr K. George.)

former Soviet Union (Danilevskii 1965, Danks 1987, Saunders 2003) and has since been detected in a calliphorid fly with a wide latitudinal range (Saunders 2001).

This type of response, in which latitude compensation is achieved by genetic heterogeneity of discrete populations, has been detected frequently in species exhibiting latitude-dependent phenology. It therefore occasioned no surprise that Norling (1984a) found such a response in *Leucorrhinia dubia*. However, this type of response is not what I postulate here as a regulating factor in the seasonal ecology of boreal Odonata.

SEASONAL ECOLOGY OF BOREAL ODONATA IN CANADA

Several species (e.g. *Aeshna septentrionalis* (formerly *Aeshna coerulea septentrionalis* Walker), *Coenagrion resolutum, Lestes disjunctus, Leucorrhinia hudsonica* and *Somatochlora hudsonica*) occur from southern BC north to tree line (Cannings 2002). Walker (1953) supposed that the northern limit of *C. resolutum* probably equated to the northern limit of Zygoptera in general. These five species are transcontinental and mainly boreal in distribution (Cannings 2002). In BC the southern limits of several species, as one would expect of predominantly northern taxa, tend to be at high altitude. All these species are widely distributed in the Yukon (Cannings *et al.* 1991). The demands of seasonal regulation upon species with this pattern of distribution must severely test their powers of adaptation and flexibility.

Progressively northern life cycles of Odonata are characterised in some species by an increase in the time taken to complete a generation (presumably reflecting the thermal budget and prey availability) and a narrowing of the range of stadia in which the last winter is spent (Norling 1984b). However, because metamorphosis and emergence are especially sensitive to low temperature, such sensitivity would seem to present a progressive constraint along a south-north gradient characterised by declining day-degree totals (Rae 1951; Boughner 1964). Some clues suggest that compensating mechanisms may be operating to mitigate the effects of such a constraint For example, Walker (1943) noted that adults of *C. interrogatum* appeared as early in the northern part of the species' range as in the south and that consequently a study of the flight period throughout its range might be rewarding. Likewise Walker (1953) noted that the flight period of *Aeshna palmata* may be earlier in Alaska than in Banff. Phenological records for 29 species (six Zygoptera and 23 Anisoptera) from nine genera (Table 1) occurring in Yukon and BC were found (in usable form) in Walker (1953, 1958), Walker and Corbet (1978) and Cannings (2002). Among these species, the recorded flying seasons begin earlier in the south than the north in 19 species (Table 1, column A) and end later in the south than the north in 26 species, a pattern conforming with expectation based solely on the thermal gradient. Two other comparisons, however, are contrary to this expectation: in nine species the flying season begins at about the same time in both the south and north (column B); in six species it begins in both places at the same time but ends later in the south (column C); and in one species (*Aeshna septentrionalis*) the recorded flying season begins *later* in the south (column D). Indeed, Cannings (2002) regards *A. septentrionalis* as the most boreal of Canada's darners.

THE HYPOTHESIS

We have noted examples of insects (e.g. Lepidoptera) in which phenology is made appropriate to latitude by discrete, regional populations exhibiting different, genetically determined response-thresholds to photoperiod that induce or avert diapause (Danilevskii 1965). In such instances it appears that the latitude-compensation may or may not be discontinuous. If discontinuous it can be manifest (along a latitudinal cline) by the existence of races, each adapted to a specific region. There is, however, another, simpler

way in which a photoperiodic response might achieve the compensation for latitude which may be occurring in western Canada.

For two reasons I accord preference here to this alternative hypothesis: first, it does not require the assumption that the responses of populations at different latitudes differ; and second, it postulates a single, unitary response to photoperiod that will result in seamless compensation at all latitudes.

Many years ago (Corbet 1962), perhaps stimulated by Walker's comment about *C. interrogatum,* I theorized that a compensating mechanism might exist whereby, mediated by a response to photoperiod, some Odonata might be able to adjust the rate of seasonal development to latitude. Until now I have been unable to visualise the nature of such a mechanism. My failure to do so in 1962 may have been because I was seeking an all-or-nothing *threshold* response to photoperiod rather than a response manifest in a gradual change in developmental rate.

The hypothesis I now postulate is that:

Some, perhaps many, species of Odonata possess a fixed response whereby the rate of larval development is positively correlated with photoperiod and that, in consequence, emergence at high latitudes occurs earlier than it would have done in the absence of such a response.

THE EVIDENCE

In some species of insects development is accelerated under long photoperiods (the light-growth [LG] effect), although in others long photoperiods have the opposite effect (Saunders 2003). The LG effect is well known but apparently no one has yet suggested that it could play a seminal role in adjusting phenology to latitude. Many species of Odonata exhibit the LG effect (see Danks 1987; Corbet 1999). For example in late-stadium larvae of five species of Zygoptera and the anisopteran *Epitheca* (formerly *Tetragoneuria*) *cynosura* (Say) the rate of development in several late stadia is directly proportional to photoperiod (Jenner 1958); and Dennis Procter (1973) concluded that in BC (at 49°19'N) an increase in (absolute) photoperiod at low temperatures can increase developmental rate as effectively as can a temperature rise in late stadia of *Enallagma boreale*, *Leucorrhinia glacialis* Hagen and *Libellula quadrimaculata.* If we allow the possibility that odonates respond to *changing*, as distinct from *absolute*, photoperiods (see below), then we note from Fig. 3 that the former variable, also, shows a latitude-dependent regression. This variable, manifest as *rate* of change, would also provide a mechanism for enhancing rates of development in spring in northerly populations.

The considerations above apply with particular force to T2 species and to the responses to photoperiod of the last three or four stadia. A somewhat different case is presented by T3 species– the obligatorily univoltine species – in which *all* larval stadia are exposed to the photoperiodic regime of spring.

A recent finding by Johansson and Rowe (1999), obtained in a different context, provides the evidence I need to formulate a hypothesis with confidence. Johansson and Rowe (1999), working in Guelph, Ontario (43°33'N) investigated the LG effect in *Lestes congener* (Hagen), a T3 species. Their hypothesis was structured around the assumption that, because the diapause eggs might hatch in early spring at different times, some larvae from eggs hatching late might find themselves with insufficient time to complete development before the season was too advanced for adults to reproduce. The authors noted that such 'late' larvae, subject to a seasonal time constraint, would be completing a given stadium later in the year and therefore under longer photoperiods than their more advanced conspecifics. As the authors' hypothesis predicted, larvae so placed compensated for their backwardness by accelerating development under long

photoperiods. Later, Johansson *et al.* (2001) demonstrated similar responses in the Palaearctic *Lestes sponsa* (Hansemann), another T3 species. Both *L. congener* and *L. sponsa* responded to long photoperiods by completing the larval stage sooner, albeit by producing smaller F-0 larvae. In the light of my hypothesis, these are significant findings, even though the authors were not addressing the matter of variations in latitude. Their results have obvious implications for a species like *Lestes disjunctus* which (in Canada) occurs from southern BC north to tree line. Eggs of this species are laid in stems of emergent plants, often above the water surface (Sawchyn and Gillott 1974) and are therefore likely to be exposed to highly variable temperatures when they hatch in spring; consequently larvae in different habitats are likely to start development at widely different times, some larvae being far in advance of others. Facing the compelling need to emerge as early as possible in the brief summer ahead, such larvae would benefit greatly from a means of compensating for late hatching. Accordingly we may expect the LG response to be present and well developed in populations of *Lestes disjunctus* also.

We have already noted that several species of Odonata respond to long photoperiods in spring by accelerating development. Two species of Zygoptera, *Coenagrion angulatum* Walker and *C. resolutum,* in Saskatchewan, show this response especially clearly (Sawchyn 1971). The seasonal progression of photoperiod is such that, for the same date in spring (after the spring equinox and before the summer solstice), the photoperiod is longer at the more northerly latitude (Fig. 1). This means that, provided that ambient temperature and prey availability are permissive, larvae possessing such a response to photoperiod will develop progressively more quickly in northerly populations, to an extent that is directly proportional to latitude. Such a (unitary) response alone would achieve the compensatory effect needed to adjust the onset of emergence to latitude, but without the need to invoke genetic heterogeneity between populations. When envisaging the effect of such a compensatory response, we should note that emergence at the highest latitudes may not necessarily be *earlier* than emergence at lower latitudes: the effect may only be that emergence is earlier than it would otherwise have been *without* the operation of a compensatory mechanism.

Implications of voltinism

Voltinism bears on the hypothesis, especially in regard to T2 species, in two respects. It may correlate with the date of first emergence; and also, as a consequence of Johansson and Rowe's (1999) findings, with *size* at emergence.

Regarding the date of first emergence, we may expect the duration of larval development of T2 species to increase with increasing latitude. Norling (1984c) found that *C. hastulatum* was mainly univoltine at 58°42' N, but that cohort-splitting occurred at a higher latitude (67^{0}50'N) so that the study population became semivoltine. This process entailed the life history changing from T2 to T1 and so must have affected the date of first emergence. In western Canada the taxa most likely to be subject to such a change are species of *Coenagrion* and *Enallagma*. In Saskatchewan, at 52°15' N, both *C. interrogatum* and *C. resolutum* are univoltine, overwintering mainly in F-1 (Sawchyn and Gillott 1975). *C. resolutum* has been found to be both uni- and semi-voltine at 51°51' N (Baker and Clifford 1981) and 51°5' N (Krishmaraj and Pritchard 1995). By analogy with *C. hastulatum* in Sweden, one might expect these two Canadian species of *Coenagrion* to become semivoltine at the highest latitudes, but the only available evidence (Cannings and Cannings 1997) indicates that, in the two species of *Coenagrion* being referred to here, univoltinism can persist in the Yukon at least as far north as Koidern (61°58' N) (Cannings and Cannings 1997). If the Cannings' (1997) observation is representative, a response to photoperiod may be affecting development rate in early stadia also, enabling larvae to grow more rapidly during their first summer and enabling them to overwinter in stadia late

enough to permit emergence in the next spring. If such a latitude-compensation effect influences development rate in early stadia, it could offset the tendency for voltinism to increase with latitude in T1 and T2 species. Then the change in voltinism with latitude would be less pronounced in the presence of a latitude-compensating response.

Regarding size at emergence, if there were to be *no* change in voltinism with latitude, one could expect F-0 larvae to be smaller at higher latitudes. However, if voltinism *were* to change with latitude, this effect might be masked or even reversed. Populations of the T2 species *Enallagma cyathigerum* in western Europe reveal a U-shaped relationship between size of F-0 larvae and latitude (Johansson 2003), an effect attributed, speculatively, by the author to the step increase in voltinism observed at about 55°N. No such transition has yet been detected among coenagrionids in western Canada. If one exists, this might influence predictions about a relationship between the size of F-0 larvae and latitude.

In the light of these observations, it would be interesting to determine whether individuals from northern populations of species occupying a wide latitudinal range are *smaller* than their southern counterparts. So far, I have found no indication in the literature that this is so, except for the observations by Walker (1912) that, in *Aeshna* spp, an increase in mean summer temperature correlates with an increase in the length of abdominal segment 3 and in the length of the female anal appendages, and that in *Somatochlora franklini* adults are largest at the species' southern limit in the interior of the continent and smallest on the Labrador coast and in the Rocky Mountains (Walker 1925). The situation may be quite different in the T1 life cycle. *Coenagrion hastulatum* in Sweden in northern populations, at 67°50' N, when exhibiting a T1 life cycle, featured F-0 larvae that were *larger* than elsewhere (Norling 1984c).

TESTING THE HYPOTHESIS

Variables to be considered

Absolute Photoperiod. To simulate photoperiod experimentally one needs to know the lower threshold of light intensity at which a larva registers light as photoperiod. The distributions in Figs 1 and 2 portray regimes of photoperiod at three latitudes derived from regarding photoperiod *either* (in Fig.1) as the interval between sunrise and sunset, moments when the zenith light intensity under a clear sky is about 395 lux, (Danks 1987) *or* (in Fig. 2) as the interval between the beginning (before sunrise) and the end (after sunset) of Civil Twilight, namely Crep 1 (Nielsen 1963), when the corresponding light intensity is about 3.55 lux (Danks 1987). However, having regard to the shaded microhabitats that odonate larvae typically occupy, the lower threshold light intensity at which they register photoperiod is almost certainly very much less than that prevailing under a clear sky (Nielsen 1963; Lutz and Jenner 1964; Saunders 2003; Corbet 1999). So the light intensity above which odonate larvae register photoperiod will probably be more closely approximated by Crep 1 than by either sunrise or sunset. Lutz and Jenner (1964) found that the response threshold of *Epitheca cynosura*, whose larvae live amongst detritus, probably lies below 0.002 lux. Accordingly, to simulate natural photoperiods, those used in an unshaded, experimental situation should be at least as long as those portrayed in Fig. 2.

Changing Photoperiod. To investigate responses to *changing* photoperiod requires so many independent variables to be allowed for simultaneously (see Tauber *et al.* 1986; Danks 1987) that such responses have very seldom been investigated rigorously. Indeed, some lists of supposed examples (e.g. Zaslavski 1988) do not distinguish between responses to gradual (i.e. natural) and discontinuous (unnatural or stepped) changes of photoperiod. Attempts to demonstrate such a response in odonate larvae have been indicative but less than conclusive (Corbet 1956b) although, from the gradual nature of

responses to photoperiod shown by *Aeshna viridis* Eversmann, Norling (1984b) inferred the existence of a response to changing photoperiod. (A response to changing photoperiod *per se* has, however, been rigorously demonstrated in the lacewing *Chrysopa carnea* [Tauber and Tauber 1970].) The latitude-dependent change of this variable (Fig. 3) suggests that, if odonates having an extended south-north distribution were to possess a response to changing photoperiod, this also would provide a means of enhancing rates of development in spring in northerly populations. Such a response might or might not act in concert with a response to absolute photoperiod.

Sun Elevation. Because it declines with latitude, sun elevation progressively extends the duration of twilight, as is evident by comparing values in Figs. 1 and 2. The effect of this variable north of about 60° becomes evident in all Figures, especially Fig. 3, as the summer solstice approaches. Fig. 3 shows that the daily increment of photoperiod changes markedly with latitude, being about 3 and 5 min per day at latitudes 50° and 60° respectively, and exhibiting an abrupt and disproportionate increase from an already higher level at 70°, as the period of continuous daylight approaches. On this account, larvae responding to increments of photoperiod will be receiving a very strong stimulus at the highest latitudes at which Odonata exist.

Microclimate. Although air temperature is inversely proportional to latitude, the temperature close to the ground is to some extent insulated from this trend because of the progressive amelioration of terrestrial microclimate caused by the declining frequency of temperature inversions, especially north of 70° N (Corbet 1969). The water temperature at the bottom of shallow ponds benefits disproportionately from this phenomenon. In a shallow, dark-bottomed pond at 81° N, after retreat of the permafrost, the water temperature (both surface and bottom) remained close to 7°C, a temperature above that of the ambient air throughout June and July (Oliver and Corbet 1966). The bottom sediment of such ponds will benefit further by being insulated from wind-chill. These effects have also been observed by Danks (1971), in a shallow pond at 75° N: they accentuate the microclimatic advantage already possessed by small bodies of water which change far less than terrestrial ones from temperate to arctic regions, the greater specific heat of water imposing a lag that moderates seasonal and diel fluctuations (Corbet 1972). Thus animals able to develop in shallow bodies of water are to some extent buffered against the lower air temperature characteristic of high latitudes.

Testing Procedure

For field studies of seasonal regulation, access to habitats that are productive and readily sampled is a prerequisite for success, a fact convincingly demonstrated in a study of *Anax junius* (Drury) in southern Ontario (Trottier 1971). The survey of BC and the Yukon (Cannings *et al.* 1991; Cannings and Cannings 1997) has established the location of breeding populations of several species over a wide latitudinal range. The logistical implications of monitoring any of these populations in a systematic way are not insignificant but, if such a challenge can be met, exciting opportunities exist for odonatologists wishing to test the hypothesis and thus to explore further Walker's enigmatic statement (1943) that northerly populations of *Coenagrion interrogatum* seemed to be emerging earlier than southern ones. Appropriate, initial steps in such an investigation might be as follows:

1) Determine the phenology of some candidate species at different latitudes. Columns B, C and D in Table 2 provide a list of potentially suitable species. Emergence could best be monitored by collecting exuviae or by recording the presence of teneral adults — methods that could be used by a nonspecialist having access to a study site. The best species to choose would be supposed T2 species having a wide latitudinal range,

e.g. *Aeshna septentrionalis, Coenagrion interrogatum or C. resolutum.* Preference should be given to species in columns B, C and D of Table 1.

2) Determine the stadium composition of larvae of such T2 species embarking on development in early spring. This information likewise could be derived from larval samples taken by a nonspecialist able to visit a study site on chosen dates.

3) Infer the voltinism of selected species by determining the stadium composition of larvae (if any) remaining in a water body just after emergence has finished.

4) Determine by laboratory experiment the duration of each (late) stadium, identified in step (2), at permissive temperatures and with prey provided *ad libitum*, , under a range of photoperiods, chosen because they occur naturally between the spring equinox and the summer solstice over the latitudinal range inhabited by the species concerned. For each species use experimental material from several populations derived from a wide latitudinal range. When designing experiments, bear in mind that the hypothesis predicts that in all larvae so derived the rate of development in a given stadium will exhibit the same correlation with a given latitude. Having regard to the threshold light intensity used by larvae to register photoperiod, recognise that photoperiods defined by the interval between the onset of Civil Twilight at sunrise and its termination at sunset (Fig. 2) are more likely to be appropriate for simulation in experiments than those defined by the interval between sunrise and sunset. Attention in experiments should be focused initially on T2 species in which several late stadia embark on development in early spring, although, as opportunity allows, it could also be informative to determine the LG responses of earlier stadia.

Completion of these steps would either falsify the hypothesis (in regard to absolute photoperiod) or allow it to be sustained.

CONCLUSIONS

The foregoing review of phenological records, life-cycle Types and photoperiodic responses of larval stadia poised for development in spring has enabled me to postulate the hypothesis that:

Some, perhaps many, species of Odonata possess a fixed response whereby the rate of larval development is directly correlated with photoperiod and that, in consequence, emergence at high latitudes occurs earlier than it would have done in the absence of such a response.

This hypothesis, which is consistent with experimental data obtained in different contexts, helps to explain, parsimoniously, how more northerly populations of a given species could compensate for declining incident solar radiation by using photoperiodic responses to accelerate post-diapause development in spring. In this way such species could emerge earlier than would have been possible had they been responding to ambient temperature alone. To test this hypothesis could throw useful light on seasonal regulation of northern insects.

Such an investigation might appeal to the investigator whose interests include natural history. To tackle it would present challenges in both the field and the laboratory; and its completion (if the hypothesis were to be sustained) would provide a secure conceptual basis for understanding how Odonata (and other insects) in northern Canada, having different life cycles, adjust their temperature-sensitive reproductive periods to the brief, late-summer characteristic of the region.

Research by Norling (1976, 1984a, b, c) has revealed a complex interplay between responses to photoperiod and temperature in the regulation of larval development of Odonata and has shown that such responses can be modified by a larva's past experience. It is not suggested that the latitude-compensation hypothesis advanced here is to any extent a *substitute* for the matrix of responses discovered by Norling but only that it may *complement* it, enhancing its effectiveness in making the date of emergence yet more appropriate to latitude. The array of other responses by which odonate larvae adjust their developmental rate to season (Danks 1991) is complex and may make it less than straightforward to isolate rigorously the compensatory response postulated in this paper.

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Distribution and life cycle of *Rhyacionia buoliana* (Lepidoptera: Tortricidae) in the interior of British Columbia

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ABSTRACT

The European pine shoot moth, *Rhyacionia buoliana* (Denis and Schiffermueller), is an exotic shoot-boring insect of hard pines in British Columbia. In 1999 infestations of this pest in native lodgepole pine were reported at a seed orchard in the interior of this province where large numbers of the shoot moth reduced seed production by damaging pollen and cone bearing shoots. *Rhyacionia buoliana* were recorded on about 80% of the trees in a lodgepole pine seed orchard in June 2000. Pheromone trap catches and weather observations over three years indicated that first, and peak *R. buoliana* flight occurred when approximately 1000, and 1680 degree-days, respectively had accumulated from January to August (using a threshold of –2.2 °C). We found no evidence of a serious threat to natural lodgepole pine stands from *R. buoliana* damage. Head capsule measurements confirmed the presence of six larval instars in *R. buoliana* in BC.

INTRODUCTION

The European pine shoot moth, *Rhyacionia buoliana* (Denis and Schiffermueller), is an important shoot-boring insect of hard pines in Canada (Syme *et al.* 1995). In the west, lodgepole pine *Pinus contorta* (Douglas) is the most affected native species, while it is most often found on ornamentals such as mugho pine, *Pinus mugo* (Terra). It was first discovered in North America in 1914 on Long Island, New York, on imported ornamental pines from Europe (Busck 1914; Green 1962; Martineau 1984). This moth was first recorded in British Columbia (BC), in Victoria, on imported nursery stock in 1925 (Ferris 1996). The first recorded outbreak on the mainland of BC occurred in 1938 when native lodgepole pine planted as ornamentals in Vancouver were attacked (Mathers 1938). By 1961 the moth had spread to the interior of BC (Harris and Wood 1967; Evans 1973). Presently the host range in the Pacific Northwest of North America extends from north of Kamloops, BC (50° 41' 40 N, 120° 27' W) south near Salem, Oregon (45° 31' N, 122° 41' W).

Rhyacionia buoliana has one generation per year in BC. Adult moths have light reddish orange and silver forewings, gray hind wings, and a wing span of approximately 19 mm. Adults emerge in late spring and early summer. Within 24 h of emergence they mate and begin to lay eggs (Ferris 1996). Eggs are laid on shoots during June and July, on or near the buds of the lower branches of host trees. Hatching occurs approximately two wk later;

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first- and second-instar larvae construct tunnel-like webs, coated with resin and debris, between needle bases and elongating shoots of the current year's growth (Syme *et al.* 1995). Initial feeding occurs on needles within these webs (Ferris 1996). Third-instar larvae exit these webs, migrate to new buds, and construct larger, resin-lined webs between buds. Larvae then bore into, feed upon and kill these buds before overwintering there (Martineau 1984). The following spring, larvae migrate to the upper branches and bore into and deform or kill elongating shoots. Here they complete the final three larval instars before pupating for about two wk (Martineau 1984).

Rhyacionia buoliana damage results in deformities such as forked or crooked stems, bushy growth, multiple tops (Harris and Wood 1967; Alvarez de Araya and Ramirez 1989; Ferris 1996), and, in commercially harvested species, lowered timber quality (Miller *et al.* 1961). Thus far, *R. buoliana* has not been considered an important forest pest in Canada, except for attacks on forest nursery seedlings; incidence on lodgepole pine in forestry settings is minimal.

However, in recent years significant damage has occurred in a lodgepole pine seed orchard in the Okanagan Valley of south central BC. In 1999, larvae of *R. buoliana* were detected in at least one shoot per tree in 25% of lodgepole pines at the Vernon Seed Orchard Company near Vernon, BC (50° 23' N, 119°33' W) (Tim Lee pers. comm. Vernon Seed Orchard, Vernon BC). This site includes 10,739 grafted lodgepole pine trees in three orchards, representing pines from three different areas in British Columbia: Bulkley Valley, Willow-Bowron and the Central Plateau. Due to grafting, trees vary in age from 70 to 90 y and height of 1 to 6 m. In 2000, the infestation increased to approximately 80% of the lodgepole pine trees. In response, orchard managers instituted a program of chemical and mechanical control in 2000 and 2001, and chemical control alone in 2002 (Tim Lee pers. comm. Vernon Seed Orchard, Vernon BC). Chemical control with a systemic spray was used in mid-July to target feeding larvae. Mechanical control consisted of clipping and removing infested shoots by hand, before *R. buoliana* adults had emerged.

Our objectives were to study *R. buoliana* in the south central interior of BC and determine: a) its current distribution using pheromone-baited traps, b) male flight activity in relation to degree-day accumulation, and c) larval development period.

MATERIALS AND METHODS

Rhyacionia buoliana distribution and flight period. Pherocon II Diamond Traps© (Pherocon Ltd, Adair , Oklahoma) containing a Pherotech© (Pherotech Ltd, Richmond, BC Canada) flex pheromone lure with 20 µg of 97:3 E-9-dodecenyl : E-9-dodecenol (Gray *et al.* 1984) were placed in areas of high lodgepole pine density in the south central interior of BC (Fig. 1) in the summers of 2001 and 2002. In 2001, 86 of the 134 traps were hung in lodgepole pine at the Vernon Seed Orchard Company, thought to be the center of the infestation. The average orchard size is 119 by 237 m. Traps were placed in 60 x 54 m spacing at a height of 1 to 2 m, close to the stem, on the northeast side for protection against the direct sun. The remaining 48 traps were placed on ornamental and native pines, primarily mugho, lodgepole and ponderosa pines, in urban and rural settings around Kelowna and Vernon. In urban areas traps were placed on mugho pine, in outlying rural areas on ponderosa pine and at higher elevations and the Vernon seed orchard, lodgepole pine. Traps were placed in trees in early May before moth flight had begun, and removed after moth counts remained zero for more than two wk. Traps were checked and cleaned twice a week; pheromone flex lures did not require changing during the study period. In 2002, the trapping program was expanded south to Osoyoos and north to Kamloops and Salmon Arm (Fig. 1). Traps were placed on accessible pine trees.

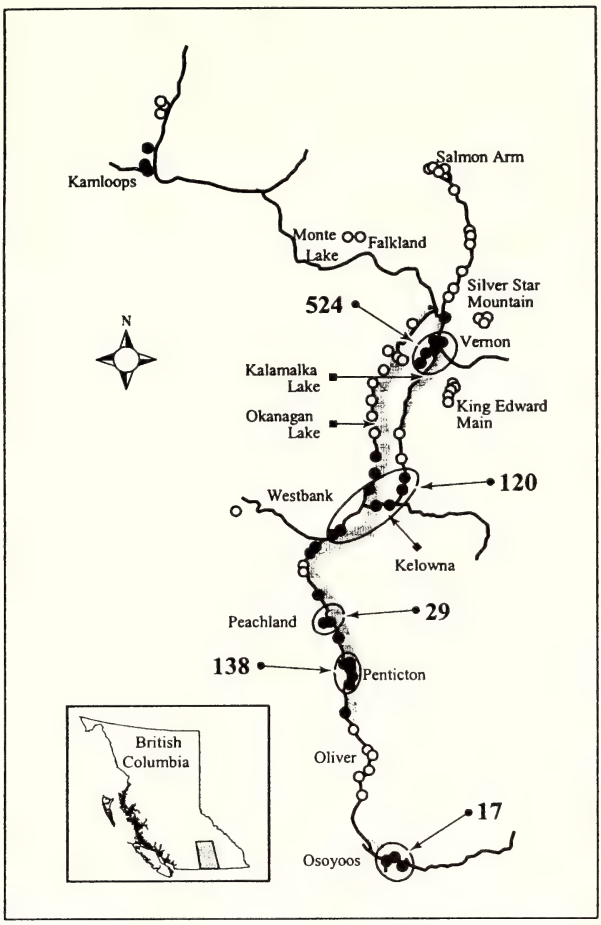

Figure 1. Location of pheromone traps used to monitor the distribution of *Rhyacionia buoliana* in the south central interior of British Columbia in 2002. Numbers with arrows attached to circles indicate number of moths caught in a group of traps. The dark gray circles indicate trap captures of more than five moths.

The 2001 and 2002 catches and flight duration at the Vernon Seed Orchard Company were compared to catch data in 2000 (data provided by CropHealth Advising and Research, Kelowna BC). Multiple years were compared to determine the repeatability of adult male captures in pheromone traps in relation to degree-days.

Degree-day accumulation. Daily minimum and maximum temperature data from Environment Canada were used to calculate degree-day accumulation from 1 January to 31 August, 2000 to 2002 using data from the Vernon/Coldstream weather station, located approximately 6 km east of the seed orchard. Regan *et al.* (1991) concluded that the most reliable degree-day calculations for development of *R. buoliana* larvae in Oregon, USA, were obtained using a minimum threshold temperature of –2.2 °C. Therefore we used this temperature and the sine method outlined by Raworth (1994) for degree-day calculations. Based on trap catches we calculated the degree-day accumulation to initial and peak flight and to various percent levels of trapped males. For 2000, pheromone trap data collected by CropHealth Advising and Research were used.

Larval development. The number and moult timing of *R. buoliana* instars were determined through larval head capsule measurements. From 27 April through 12 June 2002 fifty infested pine shoots were collected at two-wk intervals from the Vernon area

and dissected to extract and measure *R. buoliana* larvae. On 12 August 2002, samples of shoots were collected in order to obtain third-instar larvae. Larvae were preserved in glass jars with 70% ethanol. Subsequently, larval head capsule widths were measured using SigmaPro Scan© software to an accuracy of ±0.01 mm. Voucher specimens of larvae and adult moths were deposited in the Insectary at the Pacific Forestry Centre, Victoria BC (PFCI).

RESULTS

Rhyacionia buoliana distribution. *Rhyacionia buoliana* was detected in the western portion of the Vernon Forest District, and concentrated in the urban centers of Penticton, Kelowna, and Vernon areas (Fig. 1). Low populations were found in the Kamloops, Salmon Arm and Oliver urban areas. Higher elevation, natural lodgepole pine stands, such as the Rob Roy Forest Service road and King Edward main locations, yielded no evidence of *R. buoliana.* Moth populations were found to be higher in urban than in suburban areas, perhaps due to higher concentrations of ornamental pines which offer a more readily available source of food for larvae. The absence of trapped adults in high-elevation pine forests may be due to the fact that the natural stands sampled are older than the urban trees or orchard trees, and therefore, have shoots of different foliage quality. In addition, it is possible that the absence of populations in natural lodgepole stands may be due to the fact that these stands occur at high elevations, where winter temperatures often fall below the *R. buoliana* survival threshold of –22 °C (Green 1962). In 2001, two adult males were caught in two traps in outlying rural areas of Kelowna and Vernon where no exotic ornamental pines appear to occur within less than five km. This suggests the presence of *R. buoliana* in wild lodgepole pine stands. However, a comprehensive trapping in wild lodgepole pine is necessary to confirm this point.

Degree-day accumulation and flight period. Flight period of adult male *R. buoliana* in the Okanagan Valley and neighbouring areas began in mid-June and ended in the third week of July. In all study years moths began to appear in traps between Julian dates 157 and 165, or after the accumulation of approximately 1000 degree-days. Table 1 indicates degree-day accumulations required to obtain various percent levels of male captures in the south central interior of BC. Fifty percent of the total catch occurred after accumulation of 1958, 1545, and 1507 degree-days in 2000, 2001, and 2002 respectively (mean value = 1670) (Table 1). These results are comparable to values obtained by Regan *et al.* (1991) in Oregon. A quadratic curve fitted to the moth catch data for 2000, 2001, 2002 (Fig. 2) estimated that, the beginning of moth captures and peak flight occur when approximately 1000 and 1680 degree-days above –2.2 °C, respectively, have accumulated from 1 January.

Table 1.

Number of degree-days accumulated above a threshold of –2.2 °C from 1 January for different percentages of *Rhyacionia buoliana* adult males caught at the Vernon Seed Orchard Company, Vernon BC

	10%		20%		50%		90%	
Year	Julian Date	Degree Day	Julian Date	Degree Day	Julian Date	Degree Day	Julian Date	Degree Day
2000	174	1515.99	181	1680.99	195	1957.79	195	1957.79
2001	157	1166.34	172	1418.84	179	1544.54	193	1877.66
2002	168	1330.85	170	1366.20	176	1507.27	183	1649.67
Mean	**166**	**1337.73**	**174**	**1488.68**	**183**	**1669.87**	**190**	**1828.37**

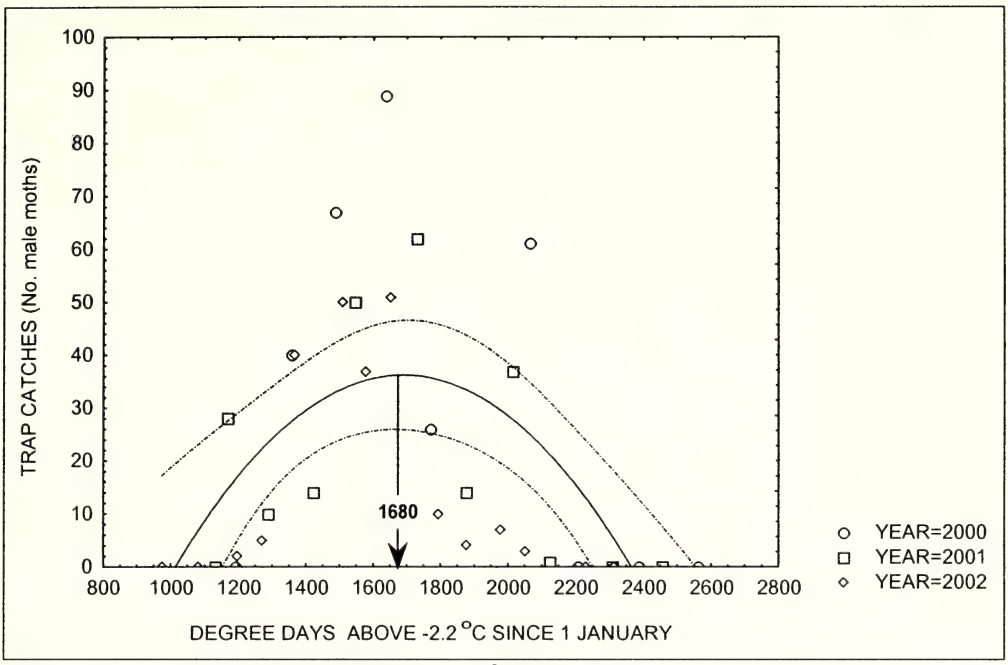

Figure 2. Degree-day accumulation (–2.2 °C threshold, 1 Jan start date) at the Vernon Seed Orchard Company for adult *Rhyacionia buoliana* catches in pheromone traps for three years (2000 – 2002). Solid curve represents fitted quadratic regression; dotted lines are the 95% confidence limits for the curve. Arrow indicates degree-days to peak emergence ($y = -7.94 \bullet 10^{-5}x^2 + 0.268x - 190$, $F = 8.91$, $df = 2, 31$, $R^2 = 0.365$ and $P < 0.0008$)

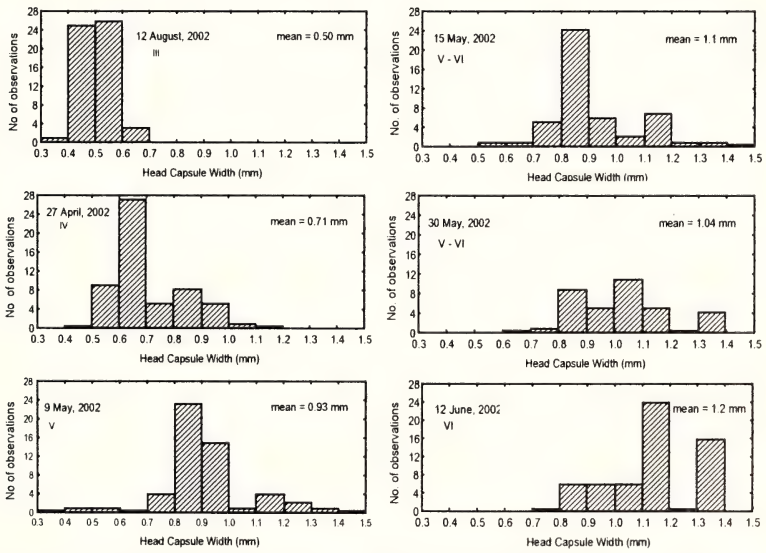

Figure 3. *Rhyacionia buoliana* head capsule widths and instar stages (Vernon BC area, 2002). Graphs arranged according to head capsule width sizes, rather than in chronological order, to depict clearly the different instar head capsule sizes. A bar represents the sum of all points in the interval. Mean head capsule widths (mm) for each instar according to Pointing (1963) are I = 0.28, II = 0.37, III = 0.55, IV = 0.64, V = 0.90, VI = 1.23.

Larval development. Comparing our head capsule measurement data to established head capsule size classes (Pointing 1963), we confirmed the presence of four of the six larval instars (III to VI) in the south central interior of BC (Fig. 3) as identified for *R. buoliana* in Ontario (Pointing 1963). The sampling period utilized in our study did not allow us to identify instars I and II. Head capsule measurements of larval samples collected on 12 August indicated a mean width of 0.50 mm, which according to Pointing (1963) corresponds to instar III (Fig. 3). Between May and June there were three instars, IV, V, and VI. The head capsule widths for instar III show a clearly defined single peak (Fig. 3). However, the frequency distribution for samples collected at all other dates exhibited a greater range of variability than instar III. This increased range in head capsule size may be attributable to larval females being larger than males; larval females may outnumber males three to one (Pointing 1963), which may result in wider head capsule distributions. Earlier instars would not have such a distribution because male and female larvae are similar in morphology.

In summary, our observations indicate that in south central BC, moth flight occurs between mid-June (Julian date 166, Table 1) and mid-July (Julian date 190, Table 1). Instars I to III occur between late July to mid-August (Fig 3). Following overwintering, instar IV can be observed in late April and instars V and VI occur between early May and mid-June. Also observations conducted in 2000 to 2002 indicate that pupation begins at the end of May and continues until early July.

DISCUSSION

Economic losses attributable to *R. buoliana* in seed orchards have not been documented in the literature, but we believe that prolonged infestations can result in economic loss due to reduced seed production and increased costs of chemical and mechanical control in order to manage this pest. Moth distribution within the western portion of the Vernon Forest District indicates the potential for an increase in shoot moth population in the Okanagan Valley. However, the winter temperatures at high elevations may limit the range at which the shoot moth can survive (Green 1962). This may account for the absence of trap catches in natural lodgepole stands, that largely occur at high elevations, such as up the Rob Roy Forest Service road, west of Falkland (Fig. 1). Since *R. buoliana* is likely to continue to damage lodegpole pine trees at the Vernon Seed Orchard Company and may affect other sites, we recommend that surveys be conducted on other lodgepole pine seed orchards in the area, as well as in neighbouring natural and planted pine plantations, including Christmas tree plantations.

The information on lifecycle, periods of larval activity, and degree-day accumulation presented here can be incorporated into a management plan for effective monitoring and control of *R. buoliana* populations. Pheromone traps should be in place prior to the accumulation of 1000 degree-days above –2.2 °C (i.e. before first flight). Chemical control using systemic insecticides, if needed, should target sixth-instar larvae in late May to early June (accumulation of 973 degree-days). First-instar larvae migrating to new buds about two weeks after peak adult flight period (1680 degree-days) may also be vulnerable to systemic chemical control.

The *R. buoliana* infestation at the Vernon Seed Orchard Company might be attributed to superior tree stock, grown under optimal conditions, providing well-developed needles and buds, which make the trees more susceptible to attack. This abundant supply of susceptible food may have been a factor in the shoot moth host shift from ornamentals to this lodgepole pine seed orchard.

When *R. buoliana* was first discovered on nursery stock in BC, the likelihood of its spread to native pine plantations was considered by both the Canadian and US Forest

Service's (Harris and Wood 1967, Howard 1963). After noting that attacks concentrated mostly on ornamentals and did not pose a threat to native pine plantations, interest in this insect decreased. However, with increased planting of genetically improved, fast-growing lodgepole pine, the increased reliance on site amelioration, and the potential for climate change to create a favorable environment, the ability of this exotic insect to increase its range and cause serious economic damage in forestry settings must be considered.

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Impact of the western balsam bark beetle, *Dryocoetes confusus* Swaine (Coleoptera: Scolytidae), at the Sicamous Creek research site, and the potential for semiochemical based management in alternative silviculture systems

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ABSTRACT

Two pre-harvest baiting regimes were tested for their effect on *Dryocoetes confusus* in select stands at the Sicamous Creek Silviculture Systems Project. Single tree and two-tree bait treatments, in addition to a control area, were established in a grid format throughout the research area. There were significantly more new *D. confusus* attacks in the baited areas than in the control area. Eighty percent of mass attacks occurred within 9 m of single tree bait centres, while 75% of mass attacks occurred within 10 m of two-tree bait centres. Baiting appears to concentrate attacks into a discrete area and therefore could be used in single tree selection or patch cut systems (cuts generally less than 5 ha in size), two of the silviculture systems applied at the Sicamous Creek research area. Of 136 dead subalpine fir trees felled and examined, 105 (77%) showed clear evidence of *D. confusus* attack, making it the major cause of sub-alpine fir mortality at the Sicamous Creek research site. Naturally attacked trees had more advanced brood development and beetles utilized a greater percent of the total tree bole but had lower attack density (number of *D. confusus* galleries per unit area) than was observed on baited trees. In baited trees, the higher attack density resulted in indistinct gallery systems due to space competition of the brood. This suggested that there was a limited acceptable area for attack in these trees, which would not normally be susceptible. This study concludes it is possible to reduce resident populations of *D. confusus* by varying the number and placement of bait trees as a pre-harvest treatment.

Key words: *Dryocoetes confusus*, western balsam bark beetle, pheromone baiting, *Abies lasiocarpa*, subalpine fir

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INTRODUCTION

The western balsam bark beetle, *Dryocoetes confusus* Swaine (Coleoptera: Scolytidae), is the most destructive insect pest of subalpine fir, *Abies lasiocarpa* (Hook.) Nutt., in British Columbia (Garbutt 1992; McMillin *et al.* 2001). Subalpine fir is also susceptible to a variety of other disturbance agents, including other insects, root and butt rots, stem rots and windthrow (Kneeshaw and Burton 1997). Cumulative mortality due to *D. confusus* may reach significant levels in chronically infested stands (Garbutt and Stewart 1991), however *D. confusus* outbreak dynamics appear to be very different from other tree-killing bark beetles. Over time, aerial overview surveys have established an average annual loss of 4.2 m^3 per hectare in older affected stands. *D. confusus* can kill many trees in a single year but usually less than 5% of any given stand is attacked in one year (Garbutt 1992). Beetle populations can persist for many years in a stand slowly killing the entire mature and semi-mature component of sub-alpine fir (Garbutt 1992).

Subalpine fir comprises 12% of total timber volume (trees cut) in B.C. (B.C. Ministry of Forests 1993) and has typically been harvested in conjunction with higher valued spruce. As low elevation stands consisting of other tree species are depleted, the number of subalpine fir sites harvested has increased. In 1990, (B.C. Ministry of Forests 1992) subalpine fir comprised 8% of total volume harvested in the interior of B.C. compared to 10.9% volume in 2000-01 (B.C. Ministry of Forests 2001). As harvesting increases in subalpine fir sites, additional research is needed to develop more effective and ecologically sensitive management strategies.

In 1990, the B.C. Ministry of Forests established a silviculture systems project at Sicamous Creek near Salmon Arm, B.C., to address ecosystem responses to a wide range of disturbance levels created by harvesting. The Sicamous Creek site is located within the Engelmann Spruce- Subalpine Fir wet, cold subzone (ESSFwc2) (Lloyd *et al.*, 1990), which is the largest of the seven ESSF subzones in the Kamloops Forest Region. This study was established at the Sicamous Creek research site to test how two baiting techniques could be used to manage *D. confusus* under different harvesting regimes.

Baiting trees with semiochemicals as a pre-harvest containment and concentration tactic is a well established pest management methodology for other bark beetles such as the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, (Borden 1990; Maclauchlan and Brooks 1999) but has not been developed for *D. confusus*. Therefore, a trial was developed to test baiting systems that could be used in a single tree selection and patch cutting harvest scenarios.

Our objectives were to: assess past infestations of *D. confusus* at the Sicamous Creek Silviculture Systems Project; test the efficacy of pre-harvest baiting systems for *D. confusus* in different silviculture systems; and determine if pre-harvest baiting could concentrate more beetles for removal at harvest than no baiting.

METHODS

Pre- and post-harvest levels of D. confusus

The Sicamous Creek research site is dominated by subalpine fir and Engelmann spruce (*Picea engelmanni* Parry ex Engelm.). The harvest regimes, each on 30 ha, were: 1) control/no removal; 2) single tree selection in which 33% of the volume was removed over a 30 ha area by cutting every fifth tree using faller's choice; 3) 0.1 ha patch cuts; 4) 1 ha patch cuts; and, 5) 10 ha clearcut. Each of the harvest regimes removed 33% of the volume. The area was harvested without taking into account the presence or impact of *D. confusus*, even though there was significant mortality throughout the area.

Aerial photographs (1:5,000) of the Sicamous Creek silviculture systems project for the years 1993-1995 were used to map the location of red trees over a 200 ha area. Using

1993 photographs, groups of red trees were identified and mapped on an acetate overlay. For 1994, groups of red trees adjacent to the original clusters were identified and mapped. Each cluster was coded in relation to the eventual harvest regime conducted in the winter of 1994-1995. The red trees mapped from the 1995 photographs were used to compare the relative efficacy of the five cutting regimes in removing *D. confusus*. The uncut strips of trees between the 0.1 ha and 1.0 ha patch cuts were located on the photographs and assessed for red trees.

Infestation characteristics

Prior to adult emergence in the spring of 1995, 15 red, 31 grey and 90 older snags, were felled and examined for evidence of *D. confusus* activity. The following characteristics were measured or noted in the red and grey trees: diameter at breast height (d.b.h.) of the bole and distance from the ground for upper and lower limits of attack; resinosis typical of *D. confusus* attack; exit holes; and the presence of live adults, pupae and larvae. Because snags were usually quite degraded, only the presence or absence of *D. confusus* galleries, exit holes and associated resinosis were recorded and measured in those trees.

Pheromone baiting trial

In June 1995, a baiting trial was established at Sicamous Creek. Two treatments and a control area were laid out. The aggregation pheromone (±)-*exo*-brevicomin (released at 0.3 mg/24 hrs release rate) was used (Phero Tech Inc.). Baits were stapled at 1.5 m on the north side of large subalpine fir. In the single tree bait treatment, established in the single tree selection area, bait lines were 50 m apart, with baited trees at 25 m intervals in a grid pattern. In the two-tree bait treatment, established in the 0.1 ha patch cut area, bait lines were placed 33 m apart, with baits affixed every 66 m along the bait line, on two adjacent, large subalpine firs at each point. Baits on adjacent lines were offset by 33 m. In total, 86 single and 82 paired trees were baited. No baits were used in the control area. A chi square analysis was used to compare the number of green (live) trees to red (attacked) trees in the three treatment regimes.

In September 1995, a 100% ground assessment of all subalpine fir in the three study areas was conducted. Using Stock's (1991) criteria for "attack classes" in Table 1 a stem map was produced of the baited, attacked, mass attacked, red and grey trees. The d.b.h. of these trees was measured, and the number of snags in each area was counted. In each treatment, 10 randomly placed 15 m radius circular plots were established, to discern infestation characteristics. In each circular plot the d.b.h., species and tree class were recorded for each tree with minimum 9 cm d.b.h. Chi square analysis was used to compare the d.b.h. frequency distribution of red, grey and snags to unattacked trees.

Comparison of insect development on baited and naturally attacked subalpine fir

In late August 1996, 10 baited mass attacked trees in the single tree bait treatment area and 13 new mass attacked trees outside the study area were felled. Beginning at the stump (cut end of tree), gallery systems were dissected in 10×30 cm bark sections every 1.5 m along the bole. For each sample, the number of gallery systems and the occurrence of associated species were recorded. Within each gallery system, the presence or absence of *D. confusus* life stages and resin was recorded, and the length of each egg gallery was measured. Female *D. confusus* constructs the egg gallery away from the nuptial chamber where she mates and deposits eggs along the sides of these galleries. The upper bole of the tree was examined for secondary scolytids and other associated insects. These scolytids are often referred to as secondary bark beetles as they do not typically kill trees but occupy trees infested by other tree killing species of the Scolytidae. Height limits for conspicuous resin flow was also noted. Foliage colour change was rated using a six point rating system (Table 2).

Table 1

Tree classifications assigned to subalpine firs attacked by *D. confusus*. These "Attack Classes" were developed by Stock (1991) and modified by L. Harder.

Attack Class	Description
attacked	streams of resin on bole (presumed unsuccessfully attacked)
mass attacked	frass and possibly resin on bole (presumed successful intense colonization of tree)
red	red foliage present (represents old attack from which new mature beetles emerge)
grey	needles mostly gone, but fine twigs present and bark generally intact (no beetles remaining in bark)
snag	a long dead tree; minimum height 2 m and d.b.h. 12 cm, with bark loose or absent and fine twigs gone

Table 2

Foliage colour classes used to classify colour changes in subalpine fir trees one year after mass attack by *D. confusus*.

Colour Class	Description
0	No colour change noticeable
1	Red needles on some tree limbs, usually on lower bole
2	Foliage on less than ½ of the tree limbs starting to turn red, usually on lower bole
3	Half the foliage turned red
4	Most of the foliage turned red, some faded green left
5	Foliage completely red

Baited and naturally mass attacked trees were compared using a chi square test based on the number of trees containing different life stages of young brood. Samples without gallery systems, and gallery systems without brood, were classed as failed gallery systems and compared to other characteristics of attack by using a chi square test. Analysis of variance comparing naturally attacked trees and baited trees were done on gallery length, resin flow, number of egg galleries, and the total brood gallery length.

RESULTS AND DISCUSSION

Pre- and post-harvest levels of D. confusus

The mapped number of red trees decreased from 1993 to 1995 in both undisturbed and harvested areas (Table 3) indicating an overall decline in the *Dryocoetes* population. Because clearcut treatments (1 ha and 10 ha) remove all trees in an area, all *D. confusus* attacks were also removed in the harvested areas. Fewer red trees were observed in the 0.1 ha and single tree selection cut areas than in the 1.0 ha patch cut area (Table 3). The buffer strips between the 1.0 ha patch cuts were undisturbed by harvesting therefore, there was a similar level of attack there as in the undisturbed control areas. In the other two treatments, the 0.1 ha patch cut plus buffer strip and the single tree selection, there was so little area between the cuts that more attacked trees were removed at the time of harvest. Any dead trees within the narrow buffer strips, many of which were infested with *Dryocoetes*, were removed at the time of harvest. Thus, despite the lack of a conscious effort to manage for *Dryocoetes*, much of the resident beetle population was removed from these areas when harvested.

Table 3

Numbers of red subalpine fir per hectare in undisturbed and treated areas before and after treatment as seen in three consecutive years of aerial photographs.

		No. red trees per ha		
	Sample	pre-treatment	post-treatment	
Location of red trees	Size(ha)	1993	1994[a]	1995
Undisturbed control area	108	7.4	6.2	4.5
Within 10 ha clearcut	10	5.3	7.9	0
Within 1.0 ha patch cuts	9	10.1	9.7	0
In buffer strip between 1.0 ha patch cut	30	8.6	7.8	4.5
In 0.1 ha patch cut and buffer strip	18	5.5	8.9	1.3
In single tree selection area	21	4.0	3.6	0.7

[a] Road right-of-way cut through research area in 1994.

Table 4

Evidence of past attack by *D. confusus* in felled red, grey and snag subalpine fir. The characteristics assessed included *D. confusus* brood (eggs, larvae, pupae), adult beetles, galleries, exit holes made by emerging beetles and resin flow on the bole of the tree caused by attacking beetles. The number of trees having all of the above-mentioned characteristics was also summarized.

	% subalpine fir with characteristic		
Characteristic assessed	Red (n=15)	Grey (n=31)	Snag (n=90)[a]
D. *confusus* brood	27	3	0
D. *confusus* adults	13	3	0
Galleries	100	90	70
Exit holes	80	87	63
Resin flow	93	94	56
Characteristics combined	100	97	76

[a] Fewer snags were assessed for exit holes (n=87) and resin flow (n=72) than for other characteristics due to deterioration and loss of bark.

Infestation characteristics

All 15 felled red trees and 30 of 31 grey trees showed evidence of past attack by *D. confusus* (Table 4). Twelve of 15 red trees had exit holes, while only 4 of 15 had juvenile life stages, and two had adults. There was less evidence of beetle attack in snags due to deterioration and loss of bark. This is strong evidence that most of the dead subalpine fir in the study area had been attacked by *D. confusus*.

Attacked subalpine fir can retain their red foliage for a number of years prior to shedding needles and being termed grey. The examination of red and grey trees revealed that few *D. confusus* adults were still present (Table 4), suggesting that adult beetles leave red trees before trees become grey.

Successful completion of development by *D. confusus* occurred primarily along the lower portion of the bole. In general, exit holes occurred within the upper and lower limits of the gallery systems (Figures 1, 2). In 32 trees that had visible resinosis, resin flow usually overlapped the exit hole zone and in 28 trees, extended above the exit holes a few metres. There was less variation in the lower height limit for gallery systems and exit

holes than in the upper height limit. Exit holes associated with other beetles in the Family Scolytidae occurred throughout the resin flow zone extending past it in both directions. Secondary scolytids found in the lower bole were identified as *Pityokteines minutus*, and those in the upper bole as *Pityophthorus sp.*

The narrow variance in height of the lower limit of *D. confusus* galleries and exit holes, and the broader variance in diameter (Figure 2) suggest that height was of greater importance than diameter in limiting *D. confusus* occupation at the lower end of the bole. Poor gallery development between 1 and 2 m may be related to cooler nighttime summer temperatures close to the ground, typical in the ESSF (Farnden 1994). Gallery systems close to the ground at or below the lower limit of exit holes had short egg galleries. Bark in this area of the bole is often wet, encouraging the growth of decay fungi that overgrow *D. confusus* galleries. In contrast, the upper limit was characterized by wide variation in

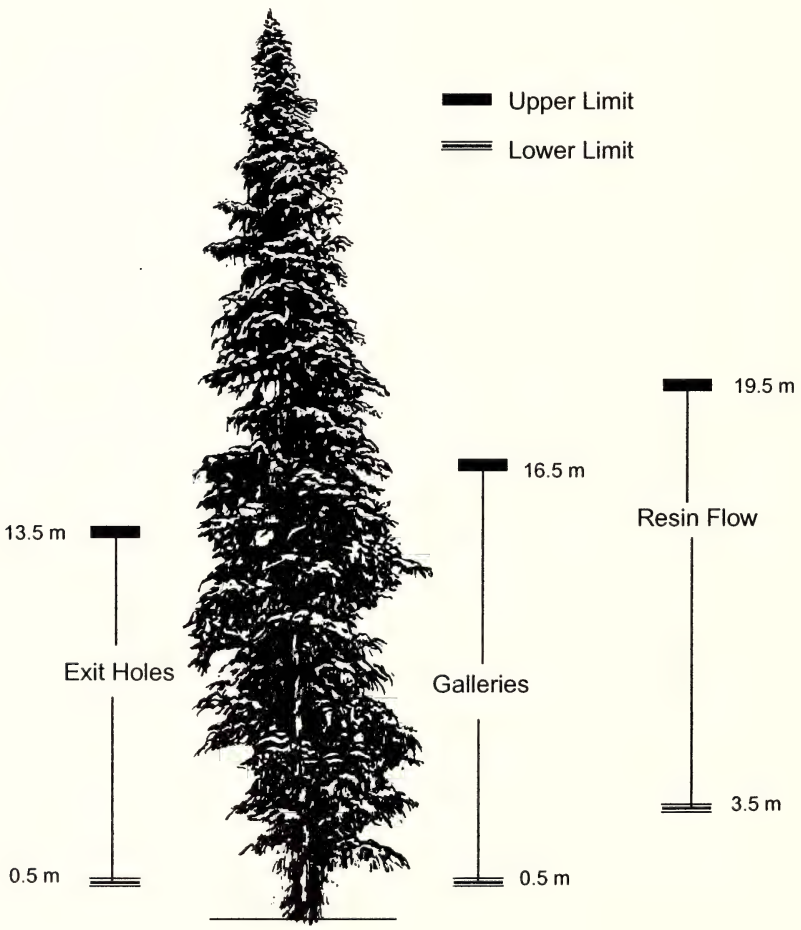

Figure 1. Upper and lower height limits for the majority of *D. confusus* galleries, exit holes, and resin flow observed on felled red and grey subalpine fir.

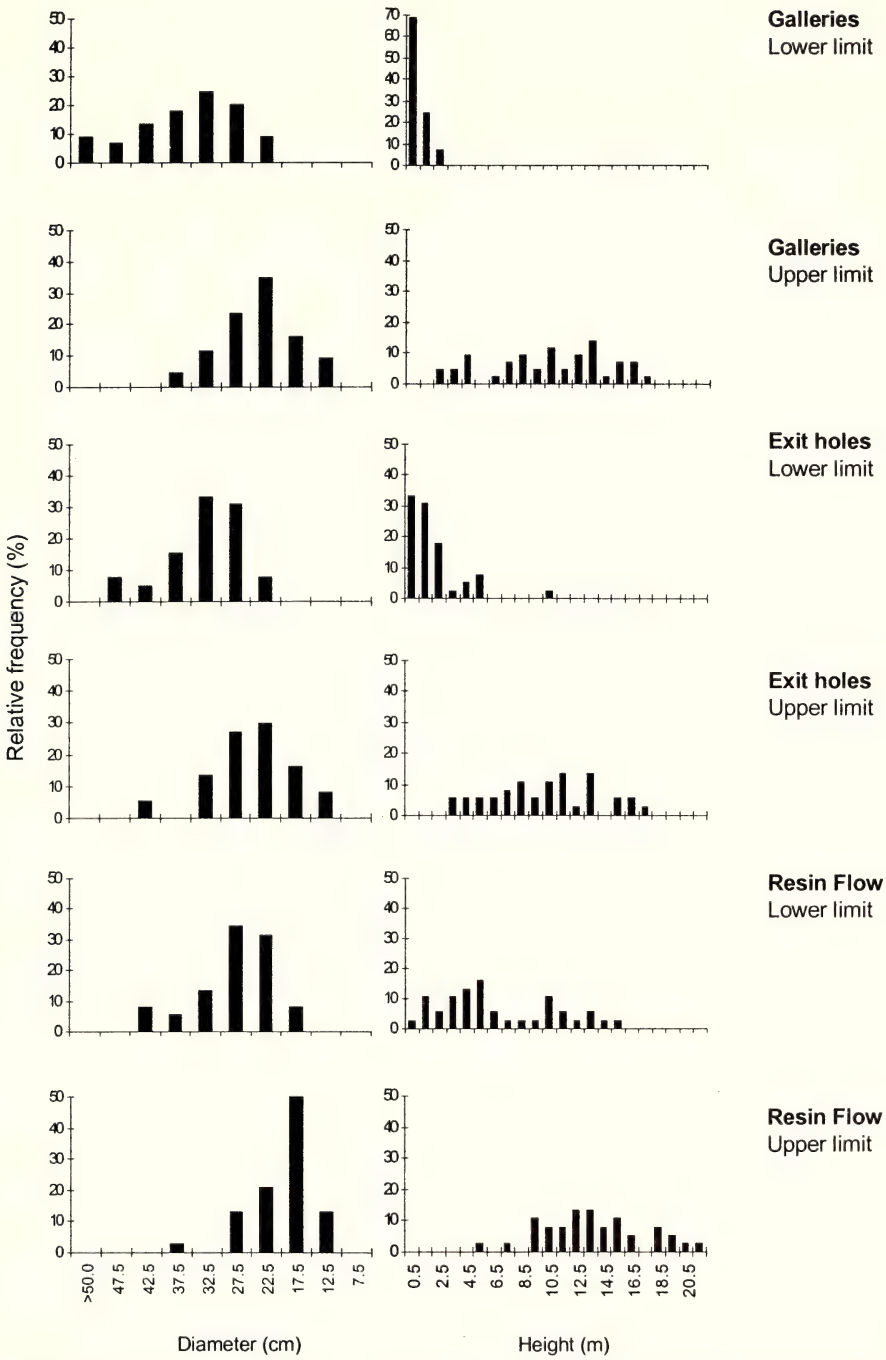

Figure 2. Frequency distributions for upper and lower limits for *D. confusus* galleries, exit holes and resin flow, based on bole diameter and height.

height, indicating a weak influence. The upper limit for resin flow, however, was tightly clustered around 17.5 cm diameter (Figure 2), indicating a possible influence related to diameter that limits *D. confusus* attack. The 17.5 cm upper limit diameter peak for resin flow was greater than the average 10 cm upper limit for attack on trees that were

previously assessed by Stock (1991). This difference may indicate a different diameter limit preference by *D. confusus* on standing trees versus downed trees.

A large percentage of subalpine fir basal area consisted of dead trees, totaling 31%, 28% and 25% for the single tree bait treatment, two-tree bait treatment and the control area, respectively, at the time of baiting. These proportions are similar to those documented by Unger and Stewart (1993) and Stock (1991). Parrish (1997) determined that losses take place over a long period in subalpine fir stands, with some existing snags having been dead for over 45 years. This slower, but continuous tree mortality affects stand structure very differently than the devastation caused by mountain pine beetle to mature pine stands.

D. confusus is likely the major mortality causing agent for standing dead trees at the Sicamous Creek research area. The d.b.h. distribution of red and grey trees contained more trees in the larger d.b.h. range (>20 cm d.b.h.), ranging in size between 19 and 49 cm, while the d.b.h. distribution of snags contained on average smaller trees, between 9 and 39 cm, similar to unattacked trees. Direct observation also confirmed *D. confusus* activity in all felled red trees, 97% of the grey trees and 76% of snags examined (Table 4). The greater percentage of small diameter trees among snags (Figure 3), suggests that the smaller trees were killed by *Armillaria ostoyae*, a common root disease of conifers. Merler (1997) found that *A. ostoyae* killed mostly subdominant balsam and spruce at this site.

Pheromone baiting trial

Baiting trial assessment. The ratio of mass attacked to red attacked trees in the single tree and two-tree bait treatments was similar, and was significantly higher than in the

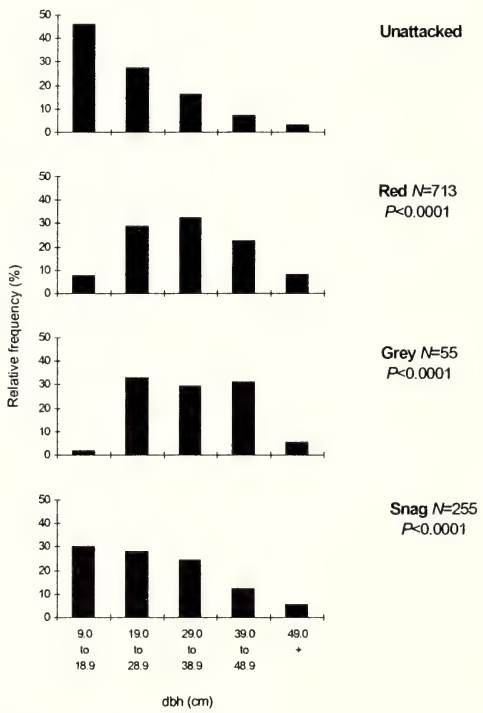

Figure 3. Frequency distribution by diameter class of unattacked, red, grey and snag subalpine fir. The DBH distribution of red, grey and snag trees were significantly different from non-attacked trees (chi square analysis).

control area (Table 5), despite differences in the numbers of red trees per hectare among the three areas in the pheromone baiting experiment. Trees in the two-tree bait treatment area were more frequently mass attacked than those in the single tree baiting area (Table 5).

Table 5

Comparison of numbers and ratios of grey, red and newly mass attacked subalpine fir in baited and control areas.

	Number of affected subalpine fir/ha				
Treatment area	Mass attacked	Red	Grey	Mass attacked: Red [a]	Red: Grey [a]
Control	4.4	18.5	15.5	0.24a	1.19a
Single tree baited	4.9	8.7	23.6	0.56b	0.37b
Two-tree baited	14.2	27.3	19.6	0.52b	1.40c

[a] Proportions followed by the same letter are not significantly different, χ^2, $P<0.001$

Single-baited trees were consistently mass attacked. Spillover attack (attack on trees directly adjacent to a baited tree, resulting from the bait treatment) was highest out to 1 m away from the bait centres (Figure 4), and decreased at greater distances. Eighty percent of mass attacks occurred within 9 m of single tree bait centres.

In the paired bait treatments, mass attacks peaked within 3 to 4 m of the bait centre, apparently corresponding to half the distance between two bait trees (Figure 4). Cumulative mass attacks increased to 60% of total mass attacks within 5 m of the bait centre. At 10 m, 75% of all cumulative attacks had been recorded.

The aggregation pheromone (±)-*exo*-brevicomin used in the baiting trial successfully concentrated *D. confusus* attacks on and around bait centres (Figure 4). However, it was unclear whether the higher ratios in the baited *vs.* control areas were caused by retaining dispersing beetles within the baited areas, attracting beetles into those areas (Table 5) or spreading the same number of beetles among more trees. Baits used for spruce beetle seem to have a limit of 25 meters efficacy (Shore *et al.* 1990), and Gray and Borden (1989) found that the influence of pheromone baiting for mountain pine beetle extended up to 75 m from grid-baited stands. Stock *et al.* (1994) observed consistently higher mass attacked to red ratios within baited blocks than in 50 m wide buffer strips surrounding the blocks. This suggests at least a 50 m range of influence on *D. confusus*.

Comparison of insect development in baited and naturally attacked subalpine fir.

There was great variation in the utilization of both baited and naturally attacked trees by western balsam bark beetle, ranging from trees with few gallery systems and little brood to those having long galleries occupying a large proportion of the bole with advanced brood development. Naturally mass attacked trees had more advanced brood development (Table 6) and a greater percentage of the bole was occupied (Harder 1998).

The average meters of egg galleries and average density of egg galleries were less in the naturally mass attacked trees than in the mass attacked, baited trees (Figure 5). Mean egg gallery length however was not different between natural and baited trees (Fig. 5) indicating more egg galleries constructed in baited trees. Some trees with low attack density had high numbers of *D. confusus* parent adults per gallery system (up to 10).
These gallery systems were stained black, evidence of the fungus *Ophiostoma dryocoetidis*. Western balsam bark beetle is closely associated with this pathogenic fungus (Garbutt 1992; Bleiker *et al.* 2003). Initial beetle attacks may be pitched out and *O. dryocoetidis* introduced, which in turn facilitates successful subsequent attack by the

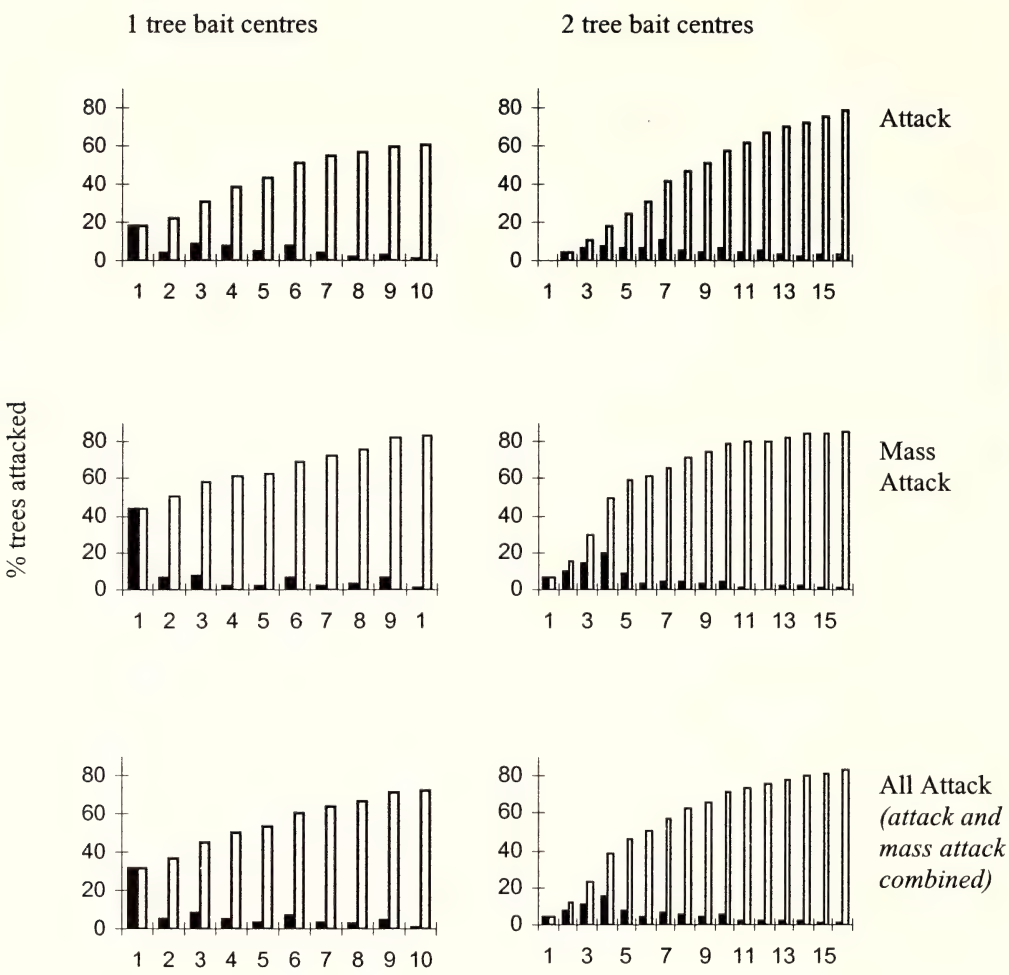

Figure 4. Distribution of attacked trees (% trees) at one bait and two bait tree centres. Solid bars indicate % attack at 1m intervals. Clear bars indicate cumulative attack.

beetle. Coalescing lesions caused by the fungus may also girdle and kill the trees without any further beetle activity (Garbutt 1992). Egg galleries were so close together in baited trees that the centre of the gallery system was completely excavated, and the nuptial chamber and brood galleries were no longer distinguishable. This high density of gallery construction and subsequent brood activity make certain characteristics of the gallery system obscure. It is possible then, that *D. confusus* was confined to a limited area in some baited trees because the tree would not have been susceptible to attack had it not been baited (Bleiker *et al.* 2003)

In 1995, colonization by secondary scolytids was limited to *Crypturgus borealis* and *P. minutus*. The year following mass attack, *P. minutus* was present in much larger numbers in half of the baited trees examined (Harder 1998). *Rhizophagus dimiatus* and *C. borealis* were found primarily in trees with advanced western balsam bark beetle brood development (Table 6). *R. dimiatus* is a bark beetle predator and may use *D. confusus* pheromones to locate its prey.

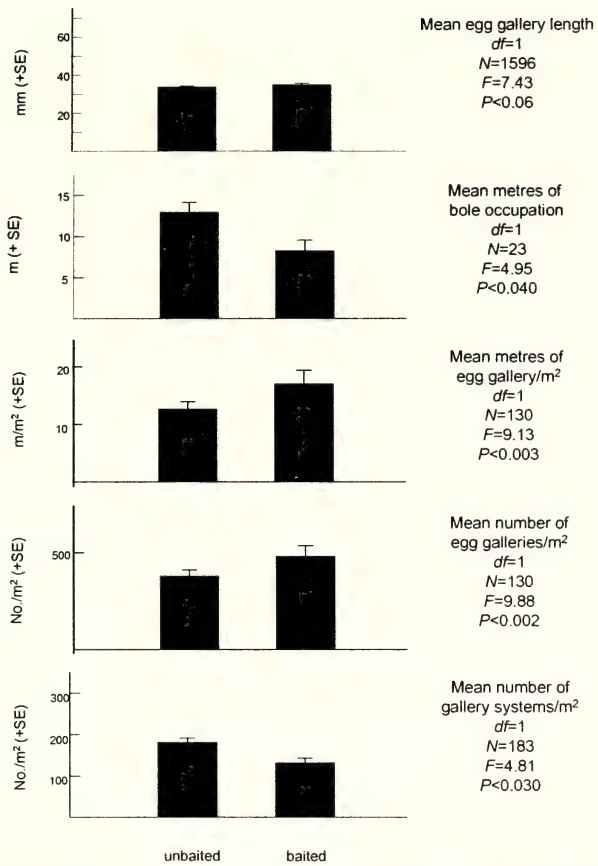

Figure 5. Comparison of mean *D. confusus* egg gallery length (cm), bole occupancy (m), and number of egg galleries per m^2 in non-baited and baited subalpine fir.

Signs and symptoms (Dissections of mass attacked trees).
Trees classified as mass attacked in 1995 were divided into those turning red and those that remained green. Fourteen trees with red foliage had larvae, evidence of successful attack, while four of the eight trees that were still green had parent adults only. Only one of these trees also had larvae, suggesting a delayed or partially successful attack. The four other green trees had no successful adult activity or brood development. In one-year-old attacks with green foliage, gallery systems from the previous year were generally abandoned, with few surviving brood. New, vigorous gallery excavation often began some distance from old gallery areas. The affected trees likely responded to pathogenic infection by producing traumatic resin at the sites of inoculation (Berryman and Ashraf 1970). New attacks were initiated elsewhere to avoid the toxic areas. The trees that were mass attacked in 1995 went through a rapid colour change between June and August 1996, from green to bright red. Because foliage does not change to red until August, aerial surveys should not be done until late summer or early fall.

The changes in foliage colour and the continued production of frass in mass attacked, baited trees one year after baiting is consistent with their original classification. Foliage colour change, frass production and renewed resinosis in trees originally classified as light-attack, indicates that adults were able to survive, while allowing a year for associated pathogenic fungi to overcome tree defenses. Lightly attacked trees could still be attractive to attacking beetles one year after baiting. In an operational setting, all mass attacked trees

Table 6

Occurrence of resin flow, *D. confusus* life stages and associated bark beetles in felled baited and naturally mass attacked trees.

Observation [a]	% Mass attacked trees affected: Baited (n=10)	% Mass attacked trees affected: Natural (n=13)	Remarks
Resin flow	30	69	
D. confusus adults	100	100	
eggs	90	92	
small larvae	60	69	
medium larvae	30	46	
large larvae	0	30	
Secondary scolytid, probably *Pityokteines minutus*	10	23	Only a few adults in newly established galleries above zone of *D. confusus* colonization.
Crypturgus borealis	40	69	Found in 100% of trees with medium or large larvae and 50% of other trees, with galleries constructed adjacent to *D. confusus* galleries, often in large numbers.
Rhizophagus dimiatus	40	76	Predaceous, found in association with *D. confusus*

[a] Small, medium and large larvae may correspond to the first three of four larval instars (Stock 1991), however head capsule measurements were not made.

should be removed at harvest. Lightly attacked trees should also be considered for removal because they could still be high risk. Heavily attacked trees turn colour quickly, whereas lightly attacked trees may require more than one year to show colour change.

Less than half of the 23 mass attacked trees felled and assessed in the single-bait and non baited areas at Sicamous Creek, had obvious signs of external resin flow originating in the year of attack (1995). Nine trees had resin flow above and overlapping the area occupied by *D. confusus*, and two trees had resin flow contained within that area. There was a greater number of gallery systems attempted in resin flow areas, but with fewer, shorter egg galleries. There were significantly greater proportions of failed gallery systems in resin flow zones compared to those in non-resinous areas (Chi square, $P<0.001$). In other words, resin flow appears to inhibit the success of egg gallery production. The invading beetles are pitched out from the tree and if the pathogenic fungus *O. dryocoetidis* is not successfully introduced, then the attacked tree will most likely survive. The presence of resin on the bole, therefore, indicates unsuccessful attack. Typically, successfully mass attacked trees do not have copious amounts of resin on the bole but instead may present a large amount of frass.

Depending on the beetle pressure in a stand and individual susceptibility of baited trees (Bleiker *et al.* 2003), attacks may range from unsuccessful or no attack, to successfully mass attacked. It appears that often in the initial year of attack, *D. confusus* will initiate nuptial chambers but very few egg galleries in the attacked tree. During the late summer flight, made up primarily of females (Stock 1991), additional females can enter existing nuptial chambers and begin excavating new egg galleries. This extended period of attack on a baited tree would, in part, explain the variability in colour change observed.

CONCLUSIONS

Harvesting removes beetle-infested trees. While eliminating all *D. confusus* infested trees in the cut areas, the 1.0 ha and 10 ha clearcuts left populations relatively untouched in the buffer strips. In harvesting the 0.1 ha and single tree selection areas, most of the snags, grey and red trees were removed in spite of the fact that logging occurred without conscious effort to remove beetle-attacked trees. In B.C., harvesting of this type requires that all dead trees be removed for safety reasons. Even without baiting, most infested trees were removed from the area, leaving a portion of new 1994 mass attacked trees as sources of new infestation. Pre-harvest baiting of these stands would have allowed removal of most new 1994 mass attacked trees as well.

While the short-term benefits of reducing *D. confusus* populations in single tree selection and patch cut systems are evident, in the long term, the possibility of windthrow exists in single tree selection and patch cut areas (Novak *et al.* 1997). Stands harvested by single tree selection may be too open (Coates 1997), while patch cut stands are fragmented and have a large ratio of edge relative to patch size (Novak *et al.* 1997). Build up of *D. confusus* populations in windthrow could possibly jeopardize the remaining standing trees resulting in populations too large for pheromone-based management. Moreover, mortality due to root and butt rot pathogens tends to increase to very high levels in stands that are partially cut (Morrison *et al.* 1991).

Pheromone baiting to manage *D. confusus* populations when conducting single tree selection or patch cut systems is recommended. By varying the number and placement of bait trees, it is possible to reduce the resident population of *D. confusus*. The attractive power of baits seems to be sufficient to draw the majority of adult *D. confusus* from buffer strips into very small areas designated for cutting. Operational tests should be done over time to develop protocols for pheromone baiting that are consistent with a wide variety of possible harvesting regimes and infestation levels.

Subalpine fir should be considered in conjunction with the many other species present in high elevation ecosystems. The relationship between *D. confusus* and root diseases should be further explored. At present, root disease induced mortality appears limited to suppressed subalpine fir and spruce (Merler 1997), in spite of long-term disturbance due to *D. confusus*. Wildlife species such as mountain caribou may depend on old growth stand characteristics (Armeler and Waterhouse 1994) in high elevation ecosystems. There are concerns that birds, such as the three-toed woodpecker depend on snags for habitat and/or food (Klenner and Huggard 1997). Backhouse and Louiser (1991) list over 90 species of vertebrates that utilize snags for a variety of purposes. A large number of invertebrates, bryophytes, and lichens are also likely to depend on large dead trees. Thus, there are many reasons to be cautious about removing *D. confusus* from *A. lasiocarpa* stands. The possible conservation importance of stands characterized by large *A. lasiocarpa* and the *D. confusus* dynamics contained within them may limit harvesting and managing options.

ACKNOWLEDGEMENTS

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Diversity, distribution and phenology of *Lygus* species (Hemiptera: Miridae) in relation to vegetable greenhouses in the lower Fraser Valley, British Columbia, and southwestern Ontario

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ABSTRACT

Lygus spp. were collected from near and inside vegetable greenhouses during three years in the lower Fraser Valley, British Columbia (BC) and in Leamington, Ontario (ON). In BC, the dominant species was *Lygus shulli*, followed in abundance by *L. elisus* and *L. hesperus*; *L. lineolaris* was not collected in the lower Fraser Valley. In ON, only *L. lineolaris* was collected. In BC, *L. shulli* was generally distributed throughout the region, whereas *L. hesperus* was captured in sweep net samples only in coastal areas. *Lygus hesperus* appeared to be univoltine in BC. All other species in ON and BC were apparently bivoltine. In ON, numbers of adults collected outside of greenhouses correlated with numbers collected inside greenhouses whereas this was not the case in BC. Differences in flight behaviour, abundance and greenhouse construction may account for this latter difference. Our results highlight the need for different approaches to IPM of pest *Lygus* species in the ON and BC greenhouse industries.

INTRODUCTION

Lygus bugs, *Lygus* spp. are important pests of crops throughout Canada (Philip 1997, Schwartz and Foottit 1998, Braun *et al.* 2001). They are known to attack greenhouse vegetable crops in both British Columbia (BC) and Ontario (ON) (Howard *et al.* 1994, Broadbent and Murphy 1997, Gillespie and Foottit 1997, Gillespie *et al.* 2000). All species that are pests seem to be associated with either alfalfa or weedy habitats and to invade from those habitats into crops (Khattat and Stewart 1980, Fye 1982, Schwartz and Foottit 1992a, Gerber and Wise 1995, Broadbent *et al.* 2002,)

In light of the recent taxonomic revision of the Nearctic *Lygus* (Schwartz and Foottit 1998) knowledge of the pest species distribution and occurrence with respect to greenhouse crops needs to be updated so that pest managers are making up-to-date recommendations. Surveys of canola have reported shifts in the complex of *Lygus* spp. (Butts and Lamb 1991, Schwartz and Foottit 1992b, Cárcamo *et al.* 2002).

The timing of adult flights and occurrence of immatures is important for making pest management decisions for crops where *Lygus* spp. are pests (Butts and Lamb 1991, Varis 1995). Yellow sticky traps are a useful tool for gathering this information (Luczynski *et al.* 1997), and are more practical than sweep net samples for evaluation of numbers in greenhouses.

The objectives of this study were to survey the *Lygus* complex associated with weedy habitats near greenhouse crops in two key greenhouse production regions, the Lower Fraser Valley, BC and southwestern ON, and to determine the phenology of the key species.

MATERIALS AND METHODS

BC 1996 Collections. In 1996, 60 collections of *Lygus* spp. adults were made at approximately two wk intervals at 22 localities throughout the lower Fraser Valley and immediate surroundings between 7 May and 19 September to determine the diversity of *Lygus* spp. in weedy habitats around greenhouses. Sampling was conducted with a standard insect sweep net; each sample consisted of 100 sweeps made in a 180° arc. Some localities were sampled at least three times, which provided a measure of changes in numbers over time.

In greenhouses, adult *Lygus* spp. were monitored using yellow sticky traps (30 x 60 cm, Phero Tech Inc, Richmond, BC) placed in each of six commercial greenhouses in the lower Fraser Valley starting on 23 April. Additional yellow sticky traps were placed on 60 cm tall posts in eight, low-growing, weedy, locations. Traps were oriented in an east-west direction. Three of these were within 10 m of greenhouses which had traps placed inside, two were adjacent to greenhouses without traps, and three were in locations approximately 1 km from greenhouses, in Agassiz, Chilliwack and Abbotsford, BC. Traps were replaced every two weeks, from 7 May to 20 September and the *Lygus* adults on the traps identified to species and counted.

BC 1997 Collections. In 1997, 25 sweep net collections were made between 2 April and 26 September, as in 1996. These collections were made in weedy habitats, generally within 100 m of greenhouses. On 29 June and 20 August, additional collections were made on east-west and north-south routes through the valley, from Ladner on the coast to Rosedale, near the head of the valley, and from Aldergrove, BC, on the Canada/US border to Mission, BC, on the north side of the Fraser River. We made 18 collections on 29 June and 23 on 20 August. The purpose of these samples was to provide data on species distribution within the Fraser Valley.

As in 1996, yellow sticky traps (30 x 60 cm) were placed on 60 cm posts at 10 locations in weedy fields and near greenhouses. The traps were changed every two weeks,

and the *Lygus* spp. collected were counted and identified. No collections were made in greenhouses.

BC 1998 Collections. In 1998, 103 sweep collections were made in weedy vegetation at 25 locations through the Fraser Valley, from 2 April to 26 September. These locations were at sites either within 100 m of greenhouse, or isolated from greenhouses by approximately 1 km. Ten of these locations were visited every two weeks from 2 April to 26 September. It was not possible to collect at every site in every interval because of rain. *Lygus* spp. adults and 4th and 5th instar nymphs were removed from the samples. The nymphs were reared in the laboratory to the adult stage on snap-beans and cauliflower pieces. The number of nymphs of each species was determined for each two week interval.

Yellow sticky traps (30 x 60 cm) were placed in nine locations within 10 m of commercial greenhouses. Traps were replaced every two weeks and the *Lygus* spp. on them were counted and identified. Inside each of these greenhouses, 10 small, yellow sticky traps (12.7 x 7.6 cm, Phero Tech Inc, Richmond, BC) were suspended on the trellis wire, 10 to 50 cm above the crop and approximately 10 m apart. These also were changed every two weeks, and the collected *Lygus* spp. counted and identified. Crops in the greenhouses (numbers of greenhouses) were tomato (1), cucumber (2) and pepper (6).

Ontario Field Survey. Surveys were conducted in three fields located at Pyramid Farm, Andrew Prytocki Farm and Chris Tiessen Farm in the Leamington area, Essex County, ON at two week intervals from 4 June to 9 September, 1997 and from 5 May through 6 October 1998. The sampling sites were < 10 m from greenhouses and in dense weed cover. On each sample date, 100 sweeps were taken at each site. *Lygus* spp. adults and nymphs were counted and identified.

Ontario Greenhouse Survey. Monitoring was conducted on greenhouse sweet pepper at one greenhouse in the Leamington area from May through October in 1997 using five small yellow sticky traps (12.7 x 7.6 cm, Phero Tech Inc, Richmond, BC) that were placed over five rows of pepper plants (total of 0.5 ha area). Traps were approximately 30 cm above the crop and traps were approximately 10 m apart. At the same time, *Lygus* spp. populations were surveyed by visual inspection of five rows of plants (212 plants/row) with four sampling units per row and five plants per unit. For each plant, the growing tip and flowers of two stems were checked for *Lygus* nymphs and adults. In 1998, monitoring was conducted from May through October, with 10 traps placed over 10 pepper rows and visual inspections of 10 rows of plants with two sampling units per row and five plants per sample unit.

Specimens and Records. Specimens of the dominant plants present in the sampled habitats were collected and identified. All *Lygus* spp. adult material was pinned and identified and voucher specimens were placed in the Canadian National Collection of Insects (Agriculture and Agri-Food Canada, Ottawa) (CNC). Historical records of *Lygus* spp. in the lower Fraser Valley were extracted from a database of records in Canada compiled by Schwartz and Foottit (1998). These records were compared with those documented during this study to determine any changes in distribution.

Data Analysis. Data were grouped by week to allow comparison between years. For each species locality data was pooled across all years for trap and sweep collections. The relationships between counts of insects outside and inside greenhouses were tested with Pearson correlation (CORR procedure) using SYSTAT 7.0 (SPSS 1997).

RESULTS

Extant Lygus. In southwestern ON, only *Lygus lineolaris* (Palisot de Beauvois) was collected over both years of sampling. Sampled weed hosts were ragweed, *Ambrosia artemisiifolia* L., smartweed, *Polygonum persicaria* L., green foxtail, *Setaria viridis* (L.) Beauv., red clover, *Trifolium pratense* L. and pigweed , *Amaranthus retroflexus* L.

In BC, *Lygus shulli* Knight, *Lygus elisus* Van Duzee and *Lygus hesperus* Knight were collected over the three year survey. Depending on location, the sampled habitats contained grasses, mainly *Festuca* and *Bromus* spp, red clover, *Trifolium pratense L.*, Dutch white clover *T. repens* L. shepherd's purse, *Capsella bursa-pastoris* (L.) Medic, chamomile, *Matricaria maritime* L., stinking mayweed, *Matricaria chamomilla* L., dandelion, *Taraxacum officianale* Weber, and various unidentified mustards (Brassicaceae). Based on the total numbers collected in sweep samples and on traps over the three years, *L. shulli* represents about 79% of the Lygus, *L. elisus* about 15% and *L. hesperus* about 6%. Individual species, however, varied in abundance at specific locations and in particular years. *Lygus lineolaris* was not collected in the Fraser Valley in 1996, 1997 or 1998.

Historical Records. Records in Schwartz and Foottit (1998) and in the North America *Lygus* database provide a historical record of the diversity of *Lygus* spp. in the lower Fraser Valley. The specimens representing the records for the Fraser Valley were validated by M.D. Schwartz, and were housed in the Spencer Entomological Collection (SMDV) at the University of British Columbia and in the CNC. *Lygus shulli* is represented by 65 specimens, collected from 1922 to 1996 and housed in both collections. *Lygus hesperus* is represented by 31 specimens collected from 1923 to 1996, all at the SMDV. *Lygus elisus* is represented by 23 specimens collected between 1923 and 1996, present in the CNC and the SMDV. *Lygus lineolaris* is represented by 27 specimens collected between 1923 and 1965 in the lower Fraser Valley, all of which are housed in the SMDV.

Distribution. In general, *L. shulli* was widely distributed in the lower Fraser Valley, and occurred in most samples and at all locations (Fig. 1). *Lygus elisus* was also widely distributed, although this species was collected in fewer locations than *L. shulli*. In contrast, *L. hesperus* was collected primarily in the locations close to the coast, with a small number of individuals occurring in scattered locations through the remainder of the region. Because *L. lineolaris* was the only species noted around greenhouses in the Ontario collections and was collected at all locations, its local distribution was not mapped.

Ontario phenology. In 1997, a few adult *L. lineolaris* were collected outdoors in June, the first nymphs were noted in early July, and the peak of the first generation appeared in early August (Fig. 2). A second generation followed in early September, indicated by an increase in nymphs in collections (Fig. 2). Collections were not continued to the end of this second generation in 1997. In 1998, a few adults were collected at the beginning of May. The first generation peaked in the middle of July and a second generation peaked around the end of September.

In greenhouses in 1997, the first *L. lineolaris* were sampled in mid June (Fig. 2). The numbers increased to about 1.8 adults per trap. A pesticide was applied by the greenhouse grower after the early June collection to reduce the numbers of nymphs on the plants. In 1998, *Lygus* adults were first seen in early May, along with nymphs. The population of *Lygus* adults increased to 3 adults/trap by the end of June. By 22 September, a second generation peaked at 3.9 adults/trap.

BC phenology. Adults of *L. shulli* were collected in sweep samples starting in May in 1996 (Fig 3A) and adults of both *L. shulli* and *L. elisus* were collected in April in 1998 (Figs. 4A, B). In 1998, nymphs of the first generation of both *L. shulli* and *L. elisus* appeared in sweep collections when the numbers of adults were low, in early June. The first generation of nymphs of *L. shulli* completed development by mid July, and nymphs of the second generation appeared in the field in late July. The first generation nymphs of *L. elisus* completed development in early July, and nymphs of the second generation appeared in late July. More adults than nymphs of *L. elisus* were caught. There was no

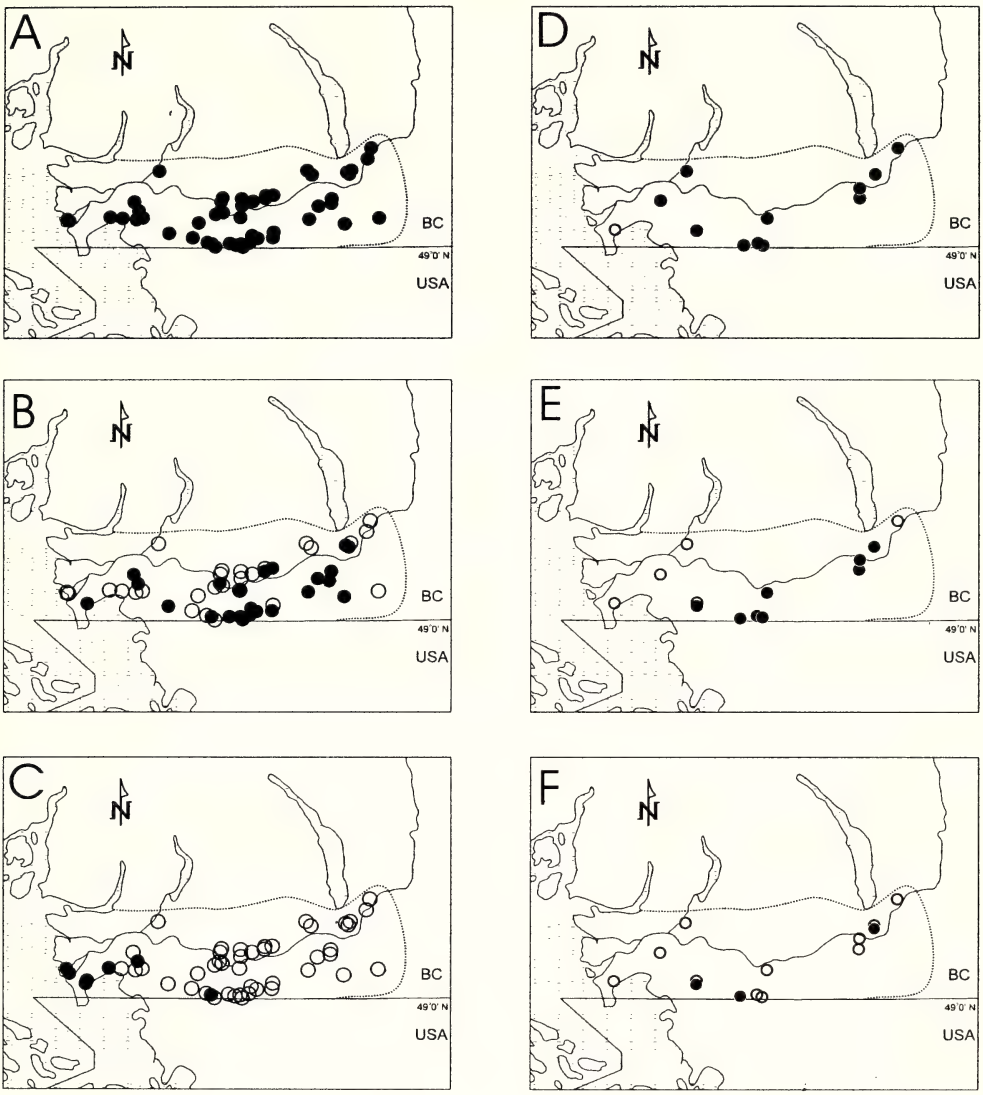

Figure 1. Distribution of *Lygus* spp. in the lower Fraser Valley, British Columbia, based on sampling in 1996, 1997 and 1998. A-C Sweep samples: A. *Lygus shulli*; B. *L. elisus*; C. *L. hesperus*. D-F yellow sticky trap captures: D. *L. shulli*; E. *L. elisus*; F. *L. hesperus*. Open circles designate locations where the relevant species was not captured, and closed circles are locations where that species was captured. The right border of the maps is at 121° 50' West. The dashed line indicates the approximate boundary of the lower Fraser Valley.

evidence of a third generation of either *L. shulli* or *L. elisus*. Adults of *L. hesperus* were collected in sweep samples only in late June and early July (Figs. 3A, 4C), and nymphs were collected only in July and August (Fig. 4C).

Sticky trap collections outside of greenhouses showed that a flight of *L. shulli* occurred in May in both 1996 and 1998 (Figs. 3, 5). These were probably adults dispersing from overwintering sites. Numbers of *L. shulli* adults on traps declined in June, increased in July

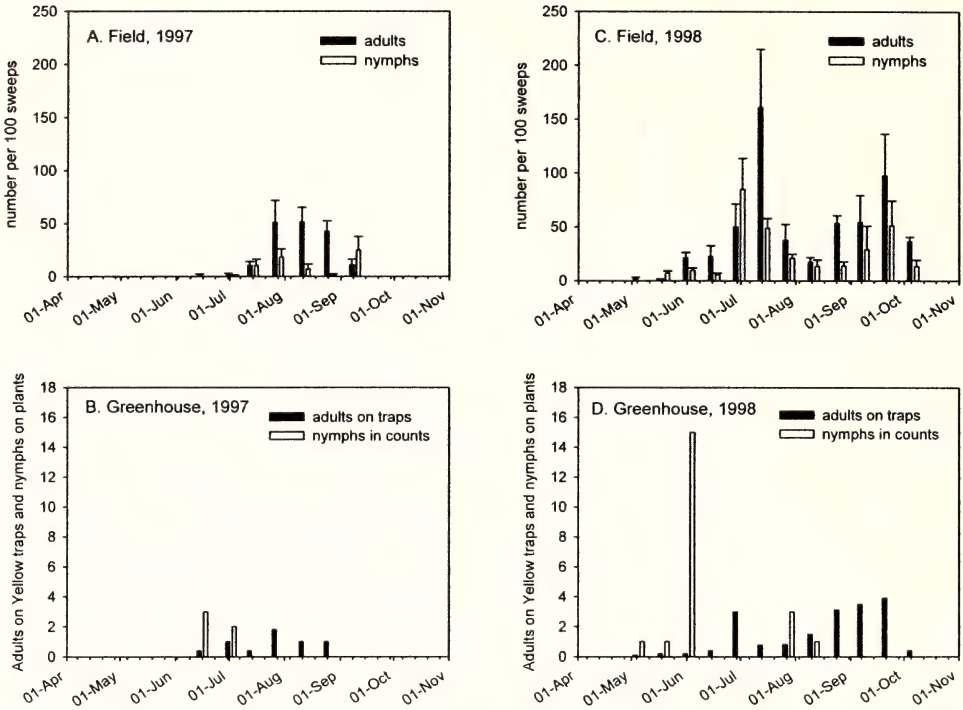

Figure 2. Numbers of *Lygus lineolaris* in sweep net samples near greenhouses, in counts on pepper plants, and on yellow sticky traps in pepper greenhouses in southwestern Ontario in 1997 and 1998. A, C: Mean number (±SE) of adults and nymphs in 100 sweeps in 1997 and 1998 respectively. B, D: numbers of adults per sticky trap and numbers of nymphs in surveys of 100 plants in 1997 and 1998, respectively.

and August, and decreased again in September. On traps outside of greenhouses, *L. elisus* also showed an early flight of overwintering adults in May (Figs. 3B, 5A). Like *L. shulli*, adults declined on traps in June and July. Adults then increased in numbers on traps in August and September, but this increase occurred somewhat later than *L. shulli*, perhaps indicating a longer developmental period. *Lygus hesperus* was never captured on traps outside of greenhouses in May (Figs. 3, 5). Adults of *L. hesperus* were noted on traps only in early August in 1996 and in August and September, 1998. The abundance of adults in sweep collections coincided with the results from traps outside of greenhouses.

Adults were relatively rare on yellow sticky traps inside greenhouses (Figs. 3C, 5B). The most abundant species was *L. shulli*, followed by *L. elisus*. Only one specimen of *L. hesperus* was captured on a yellow sticky trap inside a greenhouse. In general, captures of adults on traps inside greenhouses coincided with times when adults were captured on traps outside of greenhouses. *Lygus shulli* appeared in early May in 1996 and in mid June in 1998 in greenhouses, but *L. elisus* was not seen until mid August in 1996 and in mid June in 1998 (Figs. 3, 5). *Lygus hesperus* was not collected on traps in greenhouses in 1996, and only in late September in 1998 (Figs. 3, 5)

Correlation of field and greenhouse samples. Numbers of adults caught in sweeps outside of greenhouses in ON correlated with numbers of adults on traps in greenhouse in 1997 but not in 1998 (Pearson Correlation Coefficient (PCC) = 0.628, Bartlett's χ^2 = 10.76, $P < 0.0001$ and PCC = 0.303, Bartlett's χ^2 = 2.33, P = 0.073, respectively). No correlation was found between numbers of *Lygus* spp. adults in field sweeps and numbers of *Lygus* spp. on traps in greenhouses in 1996 or 1998 (PCC = 0.152, Bartlett's χ^2 = 0.195,

P = 0.659, and PCC = -0.074, Bartlett's χ^2 = 0.352, P = 0.553, respectively). Similarly, no correlations were found between the numbers of *L. shulli* on traps in field sites and in nearby greenhouses in 1996 or 1998 (PCC = 0.553, Bartlett's χ^2 = 1.729, P = 0.189, and PCC = 0, Bartlett's χ^2 = 0.000, P = 0.998, respectively).

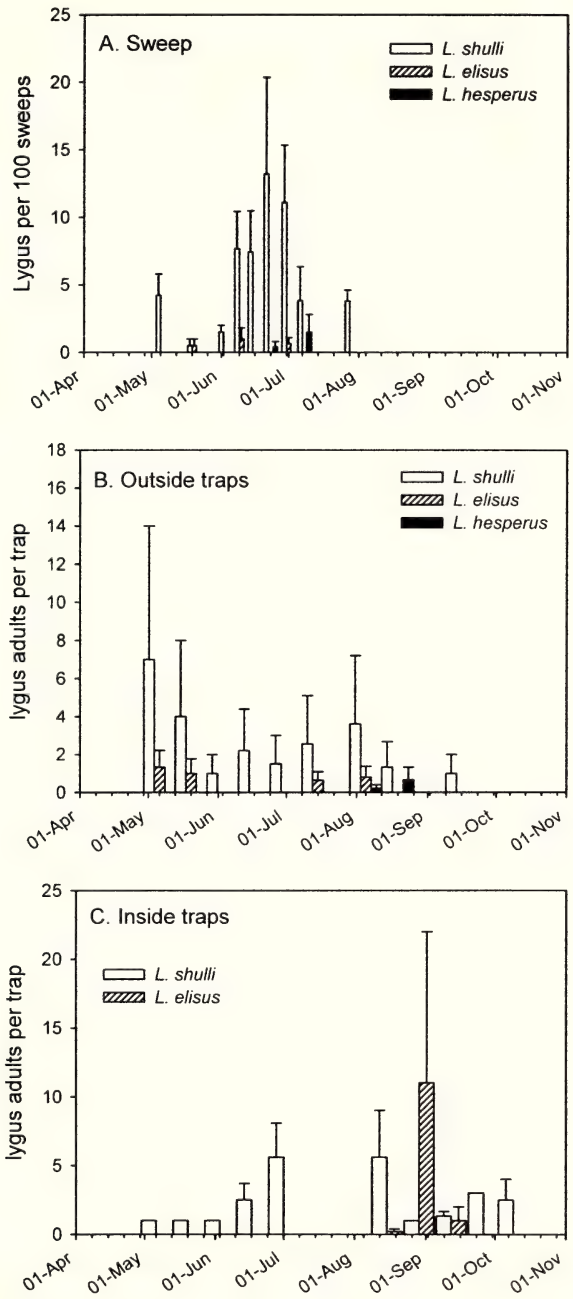

Figure 3. Mean captures (±SE) of *L. shulli*, *L. elisus* and *L. hesperus* in the lower Fraser Valley, BC in 1996. A. Average captures in 100 sweeps. B. average captures on yellow traps outside of greenhouses. C. Average captures on yellow traps inside greenhouses

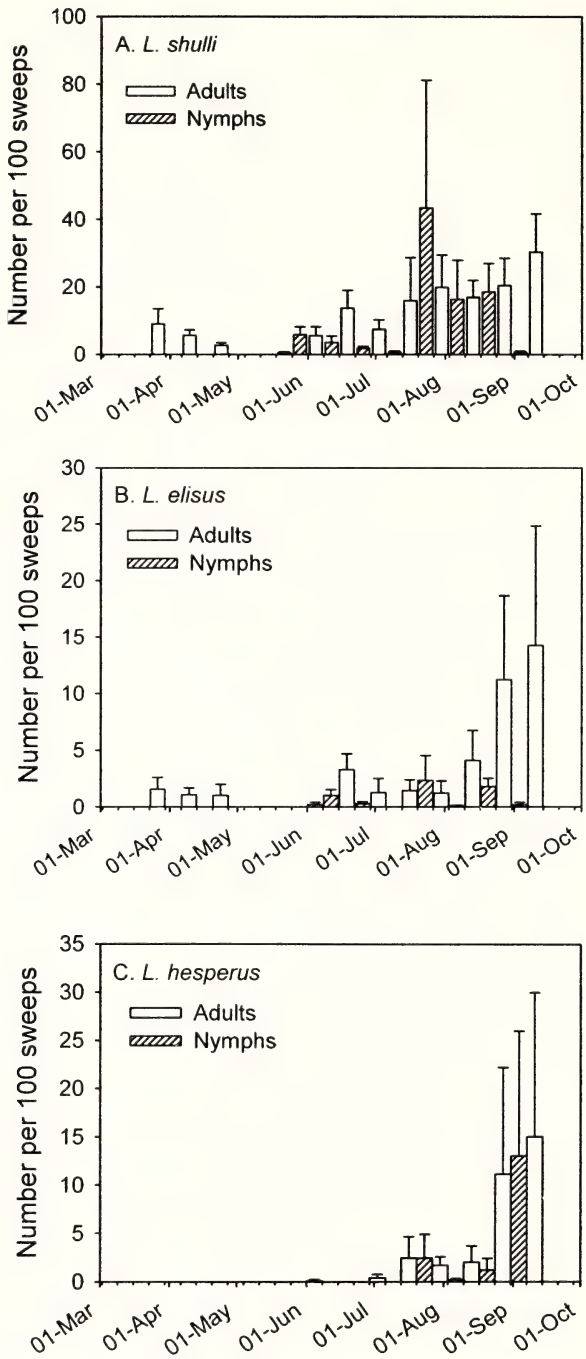

Figure 4. Mean captures (±SE) of adult and immature *L. shulli*, *L. elisus* and *L. hesperus* in sweep net samples in the Lower Fraser Valley, BC in 1998: A. *L. shulli*; B. *L. elisus*; C. *L. hesperus*.

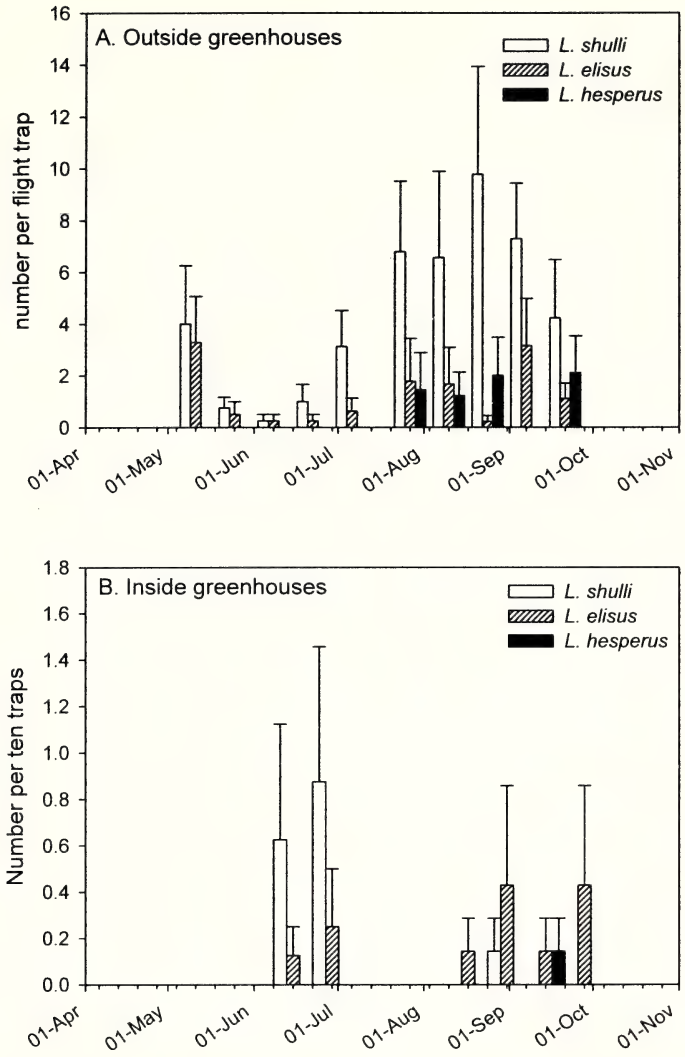

Figure 5. Mean captures (±SE) of *L. shulli, L. elisus* and *L. hesperus* on yellow sticky traps in the lower Fraser Valley, BC in 1998. A. Captures outside of greenhouses. B. Captures inside greenhouses.

DISCUSSION

The historical collection records for the Fraser Valley show that *L. lineolaris* was once one of four *Lygus* spp. in the region. This species was not collected in the current study, strongly suggesting it has either been extirpated or reduced dramatically in numbers in the lower Fraser Valley. Day (1996) noted dramatic decreases in abundance of *L. lineolaris* in alfalfa fields in eastern North America following the establishment of the exotic bivoltine parasitoid, *Peristenus digoneutis* Loan (Hymenoptera: Braconidae). Impacts of a parasitoid would not appear to be involved in BC, since a) parasitism in 1998 samples averaged only 5% by a univoltine *Peristenus* sp. attacking only the first generation (Gillespie, unpublished data), and b) *L. lineolaris* has been collected routinely in the interior and

eastern regions of British Columbia in the last decade based on collections records at the CNC.

In Ontario, numbers of *L. lineolaris* on traps in greenhouses were correlated with numbers caught in sweeps in nearby fields in one year but not in another. The correlation in 1997 may have actually been due to a pesticide application against *L. lineolaris* nymphs that were present in the greenhouse in 1997. The consequence of this was adults emerging in the greenhouse were not present and the relationship between sticky trap catches in greenhouse and field was not affected by these adults. In BC, numbers of *Lygus* spp. on traps inside of greenhouses were not related to numbers of *Lygus* spp. in sweep collections or on traps outside of greenhouses. The difference between the BC and ON results may be a consequence of either differences in species' plant location and flight behaviour, or differences in the physical structure of the greenhouses.

Little is known about host plant location and flight behaviour in *Lygus* spp. Cleveland (1982) reported that *L. lineolaris* moves from spring weed hosts into cotton fields when the latter were at the most susceptible stage. Stewart and Gaylor (1994) showed that females with chorionated eggs were more likely to fly than females without eggs, supporting observations that young reproductive females were most likely to invade crops. Rancourt *et al.* (2000) showed that flight in *L. lineolaris* was predominantly 1 m from the ground. It is possible that the species in BC differ in their host location and flight behaviour from *L. lineolaris* to the extent that they are less likely to invade greenhouses.

The flight behaviour of *L. shulli* and *L. elisus* has not been studied. Increases in the numbers of adults of both species in sweep samples preceded the increase in numbers on traps (Fig. 4A) by 2-4 weeks, suggesting that newly matured adults do not immediately move from their development locations. Adults of both *L. shulli* and *L. elisus* continued to increase in sweep samples until the last collections in late September. However, adults of both species on traps declined through September. This suggests that the sweep sample locations were also overwintering habitats, or at least very close to overwintering habitats, and that adults did not disperse from this habitat.

The greenhouse industries in the lower Fraser Valley of BC and southerwestern Ontario typically use different greenhouse structures. The Ontario industry favours double polyethylene greenhouses that have side-wall vents, that is, vents that open at or near to the ground surface. In contrast, the BC industry favours glass greenhouses that that have vents only on the roof, 4 m or more above ground level. If flight at approximately 1 m above ground level is typical of *Lygus* spp., then in Ontario, invasions of *L. lineolaris* into greenhouses through ground-level vents would be driven by field populations. In BC, invasions through roof vents or doorways would be random events and therefore unpredictable. Finally, there is a difference in the numbers of *Lygus* spp. adults in sweep samples in the field in BC and Ontario. In Ontario, captures exceeding 150 adults per 100 sweeps occurred, whereas in BC captures are typically one-tenth of that number. Thus, the differences in correlation between field and greenhouse numbers could be due to differences in field populations in the two regions making greenhouse invasion in BC less likely than in Ontario.

Cárcamo *et al.* (2002) reported wide-scale changes in *Lygus* spp. diversity on the prairies that were important for pest management. The differences in distribution of *Lygus* spp. within the Fraser Valley, an area about 150 km on an east-west axis and 50 km on a north-south axis, are also significant for pest management. Differences in abundance among the three species may cause differences in significance in certain parts of the valley. Differences among the species in behaviour, phenology or pesticide tolerances could mean that growers would have to adopt different IPM strategies for the different species. For example, *L. elisus* favours annual weedy Brassicaceae, whereas *L. shulli* prefers common Asteraceae (Schwartz and Foottit 1998).

Nymphs of *L. hesperus* did not appear in 1998 until early August, two weeks after the first adults had appeared in sweep samples and in traps outside of greenhouses. Based on this result, *L. hesperus* appears to be univoltine in the lower Fraser Valley, and does not occur in the field until after *L. shulli* and *L. elisus* have completed their first generation.

Lygus hesperus is a key pest of many crops in western North America (Kamm 1987, Ruberson and Williams 2000, Udayagiri *et al.* 2000), but in Canada, this species seems to occur primarily along the western, coastal part of the Fraser Valley, and appears to be univoltine. Thus, *L. hesperus* does not seem to be a major pest of agriculture in the Fraser Valley. Distribution maps in Schwartz and Foottit (1998) suggest that the northern limit for *L. hesperus* is in the southern BC area. This species may be univoltine in, or may migrate annually into the northern part of its range. Either explanation would account for the observed distribution.

We have shown regional differences in species distribution and phenology of *Lygus* spp. near and in vegetable greenhouses between BC and ON. These differences will result in growers taking different approaches to management of *Lygus* spp. in greenhouses.

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Abundance of *Lygus* spp. (Heteroptera:Miridae) in canola adjacent to forage and seed alfalfa

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ABSTRACT

Our objectives were to document the abundance of lygus bugs (Miridae) in canola after the cutting of adjacent alfalfa hay fields and to document their seasonal activity in canola plots grown in close proximity to alfalfa seed. Cutting alfalfa did not increase abundance of lygus bugs in nearby canola in sites near Barrhead, Alberta (1998-1999), in the Peace River area of British Columbia (2000) or near Carman, Manitoba (2001). In Saskatoon, from 1993-1995, lygus bug numbers remained at low levels in seed alfalfa and canola and there was no indication that the pest species (*L. lineolaris*) in canola moved in significant numbers from the adjacent alfalfa seed field. We conclude that alfalfa forage harvesting generally does not result in massive movement of lygus bugs to nearby canola.

Key words: Lygus bugs, canola, alfalfa, forage harvest

INTRODUCTION

Lygus bugs (Miridae) feed on actively growing meristematic tissue, particularly buds, flowers and immature seeds, which may result in economic losses to many crops throughout North America and Europe (Young 1986). In Alberta the most common *Lygus* (Hahn) species are *L. lineolaris* (Palisot de Beauvois), *L. borealis* (Kelton), *L. elisus* (Van Duzee), and *L. keltoni* (Schwartz) (Cárcamo *et al.* 2002). The latter species does not occur east of Alberta and *L. lineolaris* is rare in the mixed and short grass prairie ecoregions (Schwartz and Foottit

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1998). Lygus bugs are a primary pest of seed alfalfa in western Canada (Craig 1983) and an intermittent pest in canola (both *Brassica napus* L and *B. rapa* L) (Wise and Lamb 1998). Forage alfalfa or alfalfa mixtures are grown on over 4.5 million ha in Canada and less than 30,000 ha are grown for pedigreed seed (Statistics Canada 2001). Harvesting forage alfalfa keeps lygus bugs from reaching pest status in this crop by reducing their survivorship (Harper *et al.* 1990) or increasing their dispersal (Schaber *et al.* 1990).

Depending on the developmental stage of the lygus bug population, cutting alfalfa for hay may increase dispersal onto nearby host crops including canola. Many studies in Canada have documented the species composition and phenology of lygus bugs in alfalfa and canola; however, these studies did not investigate changes in lygus bug numbers in canola following harvest of nearby alfalfa. Gerber and Wise (1995) sugested that *L. lineolaris* first generation adults may move from plots of seed alfalfa to canola. Timlick *et al.* (1993) noted that although alfalfa is an excellent host for lygus bugs, in Manitoba, alfalfa grown for forage is usually cut by the 3rd week of June when most of the lygus bug population is at the nymphal stage (Gerber and Wise 1995). Butts and Lamb (1991), in northern and central Alberta suggested that cruciferous weeds, and not alfalfa, are likely more important sources of lygus bugs colonizing canola because alfalfa tends to harbour mostly *L. borealis*, a species that seldom dominates the pest assemblage in canola (Cárcamo *et al.* 2002). A similar argument was made by Braun *et al.* (2001) based on their studies conducted in central Saskatchewan.

The objectives of this study were to (i) compare lygus bug phenological patterns in canola plots grown adjacent to a seed alfalfa stand and (ii) determine if cutting alfalfa for hay resulted in higher numbers of lygus bugs in canola nearby.

MATERIALS AND METHODS

Lygus activity in canola adjacent to seed alfalfa in Saskatoon

Plots were seeded at the Saskatoon Research Centre farm of Agriculture and Agri-Food Canada, near Saskatoon, Saskatchewan (Fig. 1) in Ortho Clay Loam soil. Alfalfa, *Medicago officinalis* L. cultivar Beaver, was seeded in 1993 in a 0.5 ha solid block at 30 cm row spacings and at a seeding rate of 2.25 kg/ha. From 1994 to1995, an adjacent 0.5 ha block was divided into six blocks each consisting of a pair of plots, 8 m wide and 43 m long, planted to either *Brassica rapa* (cultivar AC Parkland) or *B. napus* (cultivar Legend) and separated from each other by a 1.8 m barrier of barley, *Hordeum vulgare* L. cultivar Harrington. The location of each canola cultivar within each of the six blocks was assigned randomly in each replicate in an overall randomized complete block design. On several occasions in 1993, and weekly throughout the season in 1994-1995, each canola plot and the adjacent width of alfalfa was sampled by taking five subsamples of five 180° sweeps using a standard 38 cm diameter insect net. At the time of sampling, 10 plants per species per replicate were examined and their growth stage determined according to the scale of Harper and Berkenkamp (1975). Samples were transferred to plastic bags, returned to the laboratory, and frozen prior to species determination. Subsamples were averaged to determine the number and species of lygus bug present per replicate plot.

Lygus abundance in canola adjacent to forage alfalfa

Commercial fields of alfalfa and canola (*Brassica napus* of unknown varieties) adjacent to each other or within 50 m were used in the study. Study sites were located at the northern edge of the Parkland region near Barrhead, Alberta (ca.100 km NW of Edmonton) in 1998-1999, near Fort St. John in the Boreal ecoregion of British Columbia in 2000, and in the Southern Parkland region near Carman, Manitoba in 2001 (Fig. 1). Sampling of both crops began at the late bud or flower stages of canola (3.3-4.1 Harper and Berkenkamp 1975) and

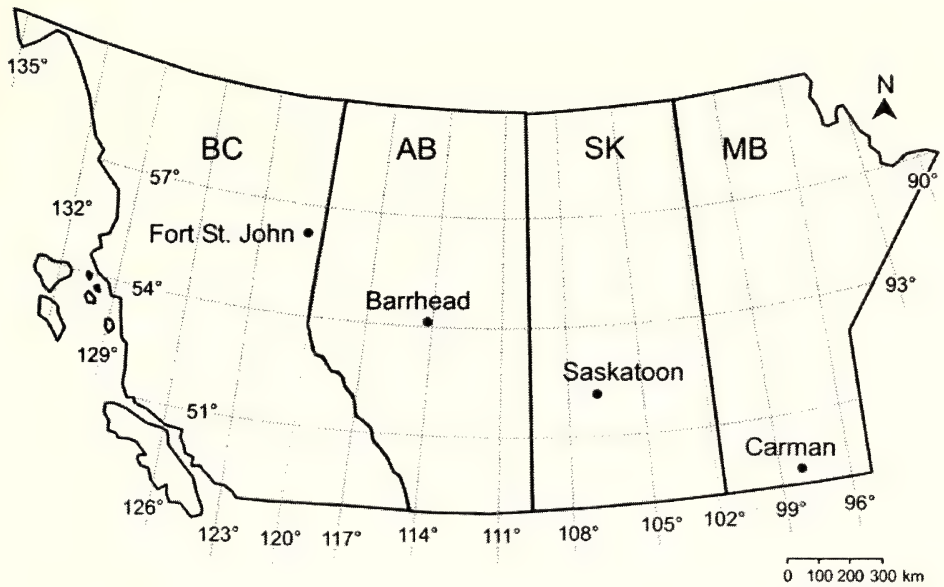

Figure 1. Location of study sites throughout western Canada used to study lygus bug abundance in canola adjacent to alfalfa.

continued weekly until one or two weeks after the cutting of alfalfa. To test the hypothesis that changes in lygus bug numbers in canola were associated with cutting of alfalfa nearby and not by some other area-wide phenomenon, fields were designated *a posteriori* as "cut" if the alfalfa was cut early or "check" if alfalfa was harvested one to two weeks later than the "cut" fields. Number of paired sites ranged from two to seven at each location and year. Canola growth stage was determined as described previously; for alfalfa, percent of the stand flowering or crop height was estimated visually.

Samples of 20 sweeps with a 38 cm sweep net were taken at five positions within each crop separated by approximately 10 m: at the edge next to the interface and at approximately 20, 40, 60, and 80 m into each crop. In 1998 at Barrhead only three positions and 10 sweeps were collected at about 10, 20 and 30 m into each crop and at Fort St. John in 2000, 100 sweeps were taken in subsets of 10 sweeps beginning about 25 m into the stand and at 10 m intervals from two sites. Sweeping efficiency is expected to differ in alfalfa and canola, particularly during the pod stages of canola when this crop is difficult to sweep. However, this should not confound results because our objectives were to compare lygus bug numbers among canola fields and not between the two crops. All fields were standard commercial size fields greater than 32 ha. All samples were stored in plastic bags and transferred to 70% ethanol in the lab for identification to species following the revision by Schwartz and Foottit (1998). Because only adults are thought to disperse long distances (Schaber *et al.* 1990), juveniles were not always kept from every site or collection and never identified to species.

Data Analysis

The number of weekly samples before and after alfalfa cutting at each canola field varied from one to three. Therefore, the average number of lygus adults per week in alfalfa before cutting and in canola before and after alfalfa cutting were calculated for the cut and check treatments and means were compared using Analysis of Variance (Statistix® for Windows, version 7). For data with heterogeneous variances, the Kruskal-Wallis non-parametric test was used.

RESULTS AND DISCUSSION

Lygus activity in canola adjacent to seed alfalfa

The abundance of lygus bugs was very low in all crops at Saskatoon in 1993 and 1994; therefore, only the 1995 data are shown. *Lygus borealis* and *L. lineolaris* were abundant in both crops and *Lygus elisus* was rare (Figs. 2a-c). The first generation adults of *L. borealis* in alfalfa peaked in early July and a smaller peak of *L. lineolaris* occurred on July 20th. Adults were observed in canola during the early flower stage in early July at the same time as first generation lygus bug adults peaked in alfalfa. However, alfalfa was not the source because the alfalfa peak involved *L. borealis* and the canola peak consisted of *L. lineolaris*. This result supports the observations by Butts and Lamb (1991) and Braun *et al.* (2001) that at some sites the two crops are dominated by different species and in such situations alfalfa may not be the major source of lygus bugs in canola. According to Gerber and Wise (1995), *L. lineolaris* populations peak in alfalfa when first generation females become reproductive and move out of alfalfa to other hosts. Our results, however, support the speculation by Butts and Lamb (1991) and Braun *et al.* (2001) that cutting alfalfa does not increase lygus numbers in canola.

Brassica napus had consistently fewer lygus bugs than *B. rapa* and alfalfa (Figs. 2b and c). Lygus bugs moved to canola starting at the bud stage and peaked during flowering. The higher abundance of lygus bugs in *B. rapa* than in *B. napus* was also observed by Butts and Lamb (1991), and can be attributed to earlier flowering in *B. rapa* and not to lygus bug feeding preferences.

Lygus abundance in canola adjacent to forage alfalfa

Lygus lineolaris was the dominant species in canola throughout the study at all sites; *L. borealis* was more abundant in alfalfa than canola and was the more common species in this crop at Barrhead in 1998 and Fort St. John in 2000 (Table 1). Other species such as *L. elisus* were rare and *L. keltoni* was found in small numbers only in Alberta and British Columbia. There were no significant differences in overall lygus bug abundance or any of the species between alfalfa fields before cutting ($P > 0.05$, ANOVA or Kruskal-Wallis test) at any of the study sites in any year. Therefore, differences in lygus abundance between adjacent canola after hay harvest were not caused by initial lygus bug numbers in the respective alfalfa fields.

Table 1

Number and percent of total (in parenthesis) of *Lygus* species at the various study sites.

	Alberta 1998		Alberta 1999		B.C. 2000		Manitoba 2001	
Lygus species	alfalfa	canola	alfalfa	canola	alfalfa	canola	alfalfa	canola
L. lineolaris	59 (40)	501 (82)	188 (70)	888 (85)	94 (47)	356 (85)	781 (91)	552 (96)
L. borealis	86 (58)	101 (17)	66 (25)	120 (12)	99 (50)	54 (13)	78 (9)	20 (4)
Total lygus adults*	149	610	268	1038	200	419	859	572
# Sweeps	850	850	1700	3000	900	1100	3300	3900

* Includes *L. keltoni* and *L. elisus*

In 1998 near Barrhead, alfalfa was cut for hay in four of the seven fields between the 18 and 24 of June. Abundance of lygus bugs in the adjacent canola fields did not change when alfalfa was cut (Fig. 3). In 1998, lygus bug populations reached outbreak levels with over 400,000 ha of canola throughout Alberta sprayed for their control. However, there were relatively few lygus bugs in the alfalfa fields adjacent to canola in our study sites. This suggests that alfalfa was not the major source of lygus bugs that colonized canola during the bud and early flower stages.

In 1999, lygus abundance for individual species or pooled totals were similar between canola fields adjacent to alfalfa that were cut in early or mid July (Fig. 4, $P > 0.05$, ANOVA

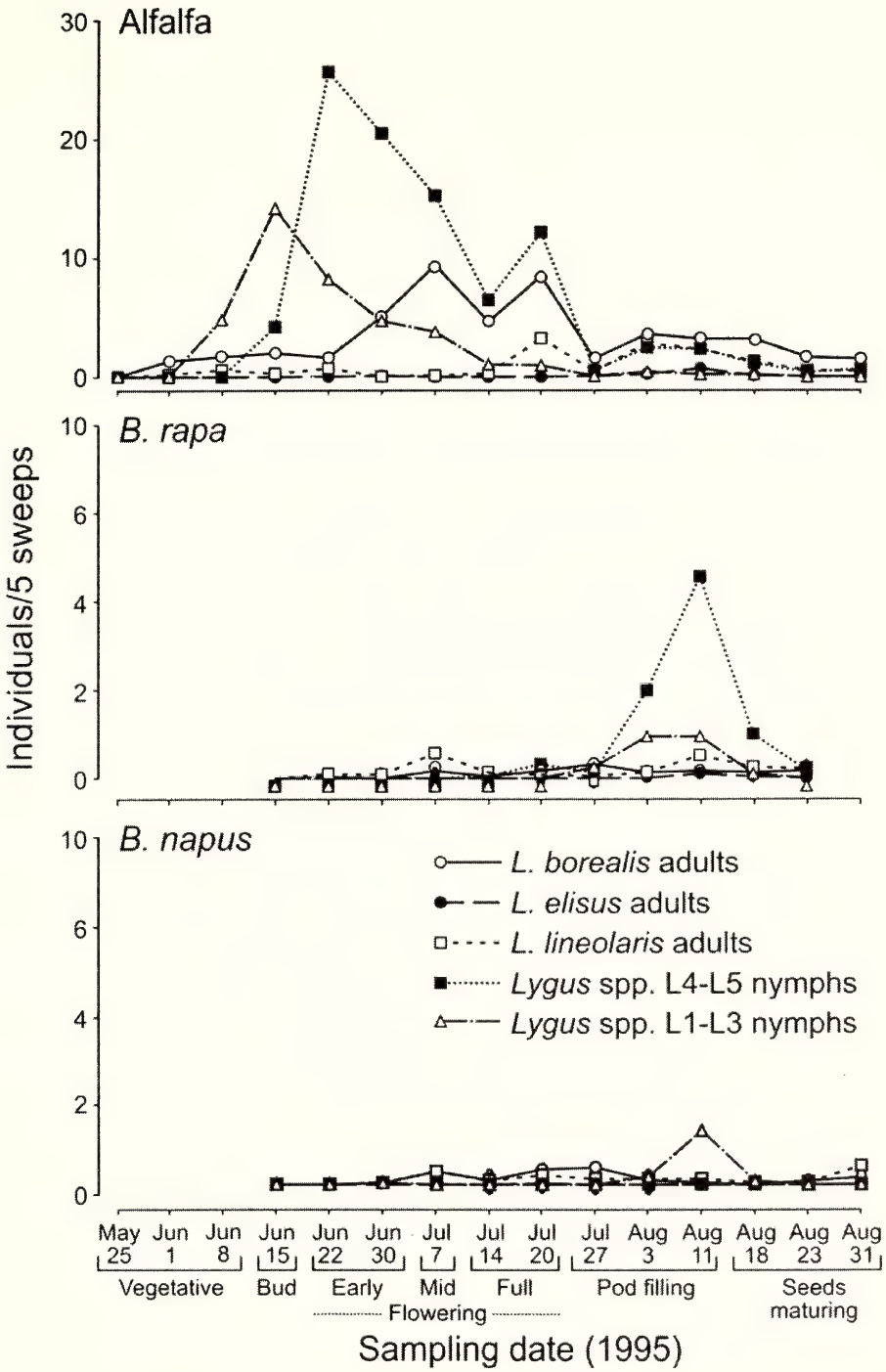

Figure 2. Lygus phenology at Saskatoon in 1995 in (a) seed alfalfa, (b) Parkland canola, *B. rapa*, (c) Legend canola, *B. napus*. Canola crop stages shown under dates.

or Kruskal-Wallis tests). Lygus abundance was lower in 1999 than in 1998, and were again lower in alfalfa than in canola early in the season. This further suggests that most lygus bugs found in canola came from sources other than alfalfa.

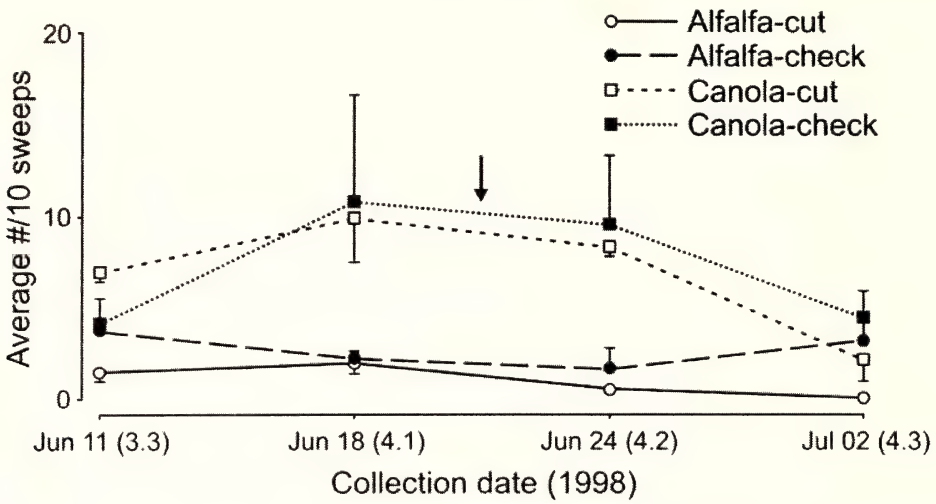

Figure 3. Adult lygus bug abundance in alfalfa and canola near Barrhead in 1998. Entries are means of 4 fields and 3 fields for the cut and check treatments, respectively ± 1 standard error of the mean. Thirty sweeps were taken per field on each collection date. Numbers in parentheses are canola crop stages (Harper and Berkenkamp 1975). Arrows indicate period when alfalfa adjacent to canola was cut.

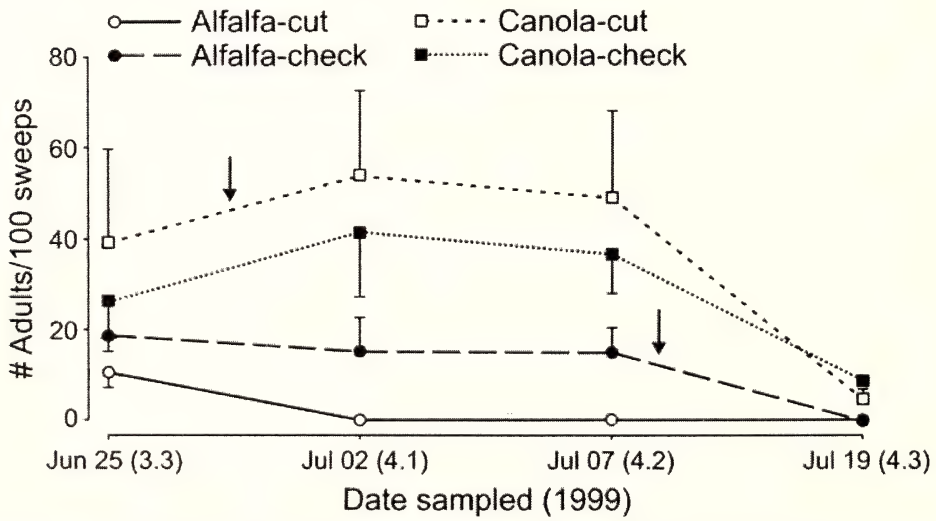

Figure 4. Adult lygus bug abundance in alfalfa and canola near Barrhead in 1999. Entries are means of 4 fields for the cut and check treatments ±1 standard error of the mean. 100 sweeps were taken per field on each collection date. Numbers in parentheses are canola crop stages. Arrows indicate period when alfalfa adjacent to canola was cut.

In 2000, flooding and frost destroyed the fields near Barrhead but two pairs of alfalfa and canola fields were sampled near Fort St. John (Fig. 5). Lygus bugs have only one generation per year in this northern agricultural region, therefore, the adults sampled were considered overwintered adults. It is unknown if these older overwintered adults are as dispersive as the parous females of the new generation (Stewart and Gaylor 1991, 1994; Gerber & Wise 1995). At Site 1 (Fig. 5) alfalfa was cut on July 21 and lygus bug adults continued to decrease in the nearby canola as juvenile numbers increased. The peak in number of overwintered adults in canola occurred towards the end of June, increasing from about 60 to 100 per 100 sweeps. A corresponding decrease from 42 to 25 adults per 100 sweeps was observed in the adjacent alfalfa (Fig. 5). At Site 2 (Fig. 5), alfalfa was cut after July 31 and a very small increase in abundance of *L. lineolaris* was observed in the adjacent canola field. The highest count, however, had occurred on the first sampling date on 7 July. As shown for Field 2 in Fig. 5, there was already a large number of lygus bug nymphs by the end of July (2 per sweep) at the time when the alfalfa was cut, indicating that the damaging populations found in canola at the pod stage had developed within the field. Lygus bug movement to canola from alfalfa or other hosts at this time was likely to be of little consequence given the large number of juveniles already present in canola.

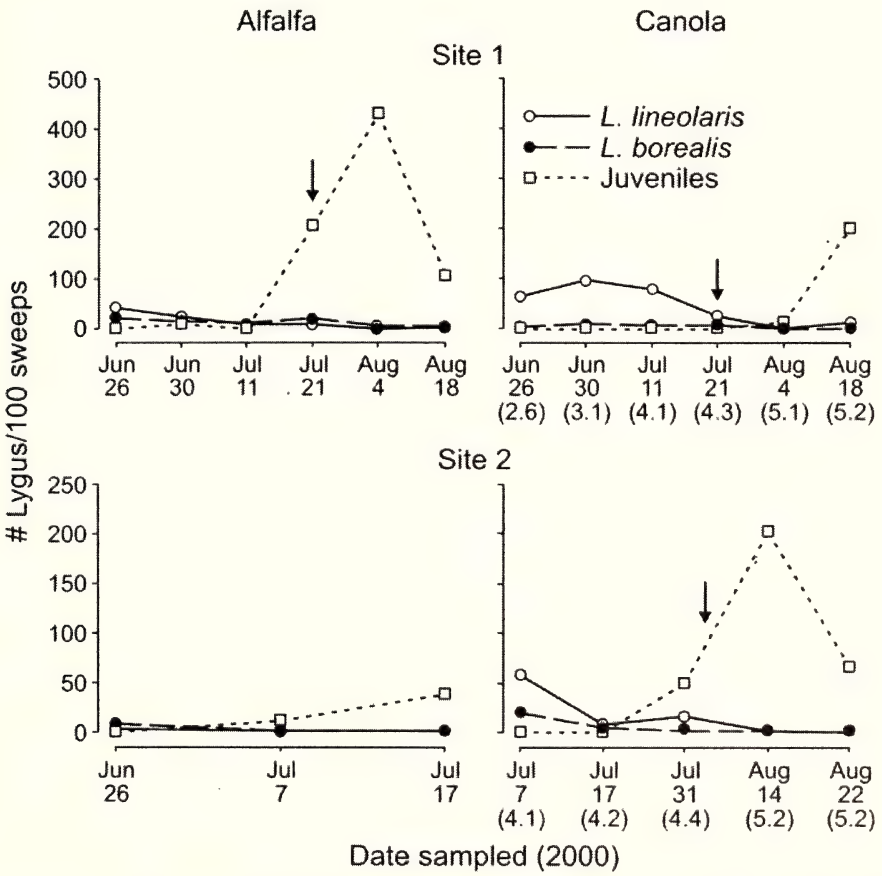

Figure 5. Lygus bugs in canola and alfalfa near Fort St. John, B.C. in 2000. Entries are total bugs caught in 100 sweeps per field at each sampling date. Numbers in parentheses are canola crop stages. Arrows indicate approximate date alfalfa was cut.

In 2001 only sites in Manitoba were sampled. Lygus bug population dynamics prior to July 10 were not studied because of late planting of canola and delayed plant growth. The abundance of either *Lygus* species or combined lygus bug abundance was the same between alfalfa fields prior to cutting it on the second week of August, or between the corresponding canola fields prior to alfalfa hay harvest ($P > 0.05$, ANOVA). On August 14-16 and August 22-23, after alfalfa was cut, weekly averages of lygus abundance was higher in canola adjacent to uncut alfalfa than in canola adjacent to cut alfalfa (Fig. 6, $F= 111.51$, d.f.= 1.5, $P < 0.01$). Average weekly numbers of lygus bugs in canola adjacent to cut alfalfa were the same before and after cutting (17 vs 8 per 100 sweeps from July 10 to August 8 and from August 14 to August 23, respectively, ANOVA, $P > 0.05$). In canola fields adjacent to uncut alfalfa, the average weekly catches for these same periods were 11 and 53 lygus bugs per 100 sweeps ($F=$ 23.7, d.f.= 1.2, $P < 0.05$). The results from Manitoba in 2001 suggest that cutting of alfalfa between August 9 and August 13 failed to result in movement "en masse" of lygus bugs from alfalfa to canola. Therefore, the risk of lygus bug damage in canola at early pod stage was not affected by cutting the adjacent alfalfa stand.

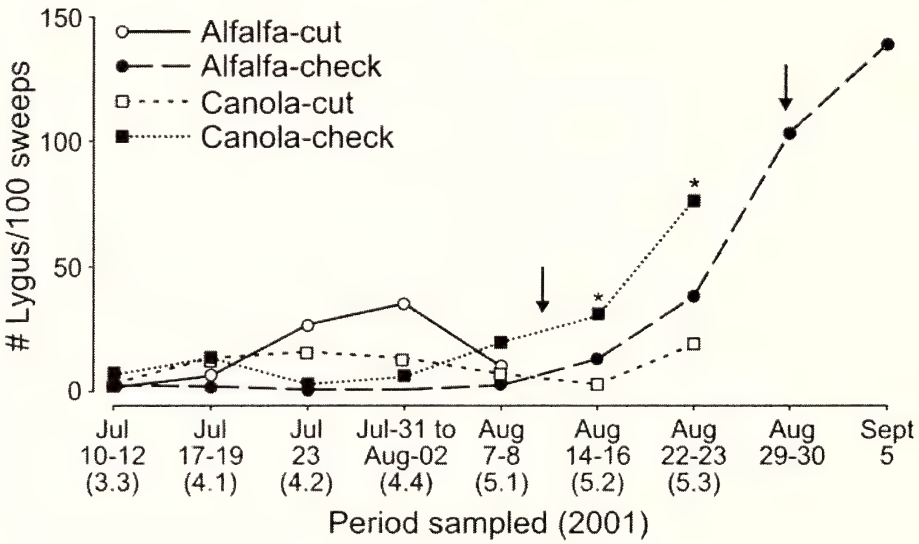

Figure 6. Lygus bug adults near Carman, Manitoba in 2001. Entries are averages for 1 to 5 fields depending on availability and access. One hundred sweeps were collected at each site on each sampling date. Asterisks indicate dates with significant differences between canola fields adjacent to cut and uncut alfalfa.

Because nymphs were not collected rigorously for the Manitoba portion of the study, it is not possible to determine if the large number of lygus adults found in canola adjacent to uncut forage alfalfa moved to canola as adults or developed within the canola stand from nymphs. It is unlikely that lygus bugs would move to canola at the pod stage since the plants may no longer be attractive (Butts and Lamb 1991). Instead, in August, lygus bugs may move to more succulent hosts to feed in preparation for the winter.

Based on the observations from sites in the Parkland and Boreal eco-regions of the prairies we conclude that cutting alfalfa in these regions does not result in massive movement of adult lygus bugs into nearby canola. These results cannot be generalized to more southern regions such as the short grass prairie of Alberta where a different species assemblage occurs and lygus bugs have 2 or 3 generations. Mark-recapture studies or molecular DNA investigations

are needed to assess the relative importance of various spring hosts as sources of lygus bugs that may reach pest status in canola in the summer.

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Influence of Trap Colour on the Capture of Codling Moth (Lepidoptera: Tortricidae), Honeybees, and Non-target Flies

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ABSTRACT

Studies were conducted to evaluate the influence of trap colour on the captures of honeybees, *Apis mellifera* L., codling moth, *Cydia pomonella* L., and non target muscoid flies in sticky delta traps. Traps varied widely in their spectral reflectance. The unpainted white and the painted white and cream traps had the highest reflectance. The painted green trap had the lowest total reflectance. The green, orange, and red traps had low reflectance at wavelengths < 560 nm. Red and green painted traps consistently caught the fewest honeybees, while the unpainted white trap caught the most. Red painted traps caught the greatest number of flies. Significantly more codling moths were caught in green and orange versus the unpainted white traps. In a later experiment, painted green traps caught more codling moths than unpainted white traps.

Key words: Colour, traps, apple, codling moth, honeybees, muscoid flies

INTRODUCTION

Optimizing trap design is vital in developing a useful monitoring system for codling moth, *Cydia pomonella* L. (Knight and Christianson 1999). The effectiveness of a variety of sticky and non-sticky trap types have been reported (Knodel and Agnello 1990, Vincent *et al.* 1990), but until recently, a sticky cardboard white or cream color wing trap has been the standard for monitoring codling moth in the western United States (Riedl *et al.* 1986). Knight *et al.* (2002), however, found that either a delta or diamond-shaped trap was more effective than the standard wing trap in laboratory flight tunnel and in field trials. We believe the delta-shaped trap has now become the most widely used trap for monitoring codling moth in Washington State. Unfortunately, early in the season the delta-shaped trap constructed from white corrugated plastic consistently catches non-target flies and honeybees, *Apis mellifera* L. Trap contamination by flies and honeybees requires that the trap's sticky liner be replaced more frequently and thus adds to the costs of monitoring codling moth.

Colour is an important factor influencing the foraging behaviour of honeybees (von Frisch 1967). Honeybees can differentiate six colour ranges between 300 and 650 nm, i.e. ultraviolet to yellow light (Burkhardt 1964). Variable degrees of contamination of monitoring traps by honeybees and bumblebees *Bombus spp.*, due to differences in trap colour have been reported (Hamilton *et al.* 1971, Gross and Carpenter 1991, Meagher 2001). In general, white and yellow traps are attractive and green traps are unattractive to Apoidea species due to their differences in spectral reflectance between 380 and 550 nm (Mitchell *et al.* 1989).

The influence of trap colour on the capture of some noctuid pests in sex pheromone-baited traps has been well studied (McLaughlin *et al.* 1975, Mitchell *et al.* 1989). However, the importance of the visual stimuli provided by traps in these two studies of night-flying moths contrasted sharply. McLaughlin *et al.* (1975) found that traps with low spectral reflectance were more effective in capturing *Trichoplusia ni* (Hübner) and *Pseudoplusia includens* (Walker), while Mitchell *et al.* (1989) found that such traps were

less effective with *Anticarsia gemmatalis* Hübner and *Spodoptera frugiperda* (J.E. Smith). Trap colour has not previously been reported to be a specific factor influencing the capture of codling moth. The objective of our study was to evaluate the influence of trap colour on the attractiveness and selectivity of delta-shaped traps for codling moth, honeybees, and non-target flies.

MATERIALS AND METHODS

Description of traps. White delta traps (Suterra, Bend, OR) were left unpainted or painted with one of five high gloss paints (Krylon , Cleveland, OH): Spring Grass green #2327, Pumpkin orange gloss #2411, Banner Red Gloss #2108, Ivory gloss #1504, and Gloss white #1501. The three darker colours were characterized based on value, chroma, and hue (Munsell Book of Colour 1976): green (4, 8, 5G), red (4, 14, 5R), and orange (6, 14, 2.5YR).

Spectral Reflectance. Trap samples (100 cm^2) were scanned with a Perkin-Elmer Lambda-9/19 spectrophotometer (Wellesley, MA) by Avian Technologies (Wilmington, OH). Trap surfaces were scanned at wavelengths from 360 to 830 nm with a monochromatic slit width set at 2 nm and operated at a scan rate of 120 nm / min.

Experiments 1 and 2. Two experiments were conducted in a 5-year-old 'Red Delicious' apple orchard, *Malus domestica* (Borkh), (mean (SE) tree height = 2.2 (0.2) m) situated 15 km east of Moxee, Washington (46°40'N, 120°05'W) at the U.S.D.A. Experimental Farm during 2003. This orchard was situated 0.6 km east of a large dairy farm. Bloom in the apple blocks at the farm occurred from 25 April – 15 May. In the first study (24 – 28 April) delta traps were not baited with a sex pheromone lure. Traps in the second study (5 – 12 May) were baited with the Biolure 10X codling moth lure (Suterra, Bend, OR). Ten traps of each colour were placed in a completely randomized design in each experiment. Unsexed, laboratory-reared codling moth adults (n = 5,000) were released into the orchard prior to the start of experiment 2 only.

Experiment 3. A third experiment was conducted to compare the attractiveness of the unpainted white and the green-painted delta traps for codling moth. This study was conducted in a 10-ha 30-year-old mixed block of 'Red Delicious' and 'Golden Delicious' situated 5 km north of Moxee, Washington (46°33'N, 120°23'W). Mean (SE) tree height in this orchard was 4.3 (0.2) m. Six traps of each colour were placed in a completely randomized design, checked every 2 to 4 d, and re-randomized. Six replicates of this experiment were conducted from 9 – 26 September. Unsexed, laboratory-reared codling moth adults (n = 5,000) were released into the orchard prior to the start of the experiment.

In all experiments, the numbers of codling moths, honeybees, and muscoid flies were counted in each trap. The predominant weather patterns during these tests were clear skies with maximum daily temperatures ranging from 20 – 32 °C.

Statistical analyses. Data were transformed with square root (x + 0.01) prior to analysis. Data from experiments 1 and 2 were analyzed with one-way analysis of variance (ANOVA). The September study was analyzed with a repeated measures design (ANOVA) across five dates. Means were separated in significant ANOVA's with Fisher's least significance difference (Analytical Software 2001).

RESULTS

The spectral reflectance pattern of delta traps differed sharply among colours (Fig. 1). The unpainted white and the painted white and cream traps were similar exhibiting > 75% reflectance at all wavelengths > 420 nm (Fig. 1). These traps had identical reflectance in the ultraviolet at 5 – 30%. Green traps had the lowest total reflectance among colours tested with a peak reflectance (ca. 20%) at 520 nm and < 10% reflectance at wavelengths <

480 nm and > 570 nm (until 810 nm). The reflectance of the orange and red traps increased rapidly at 560 nm and 600 nm and reached a plateau of ca. 55% at 620 nm and 640 nm, respectively.

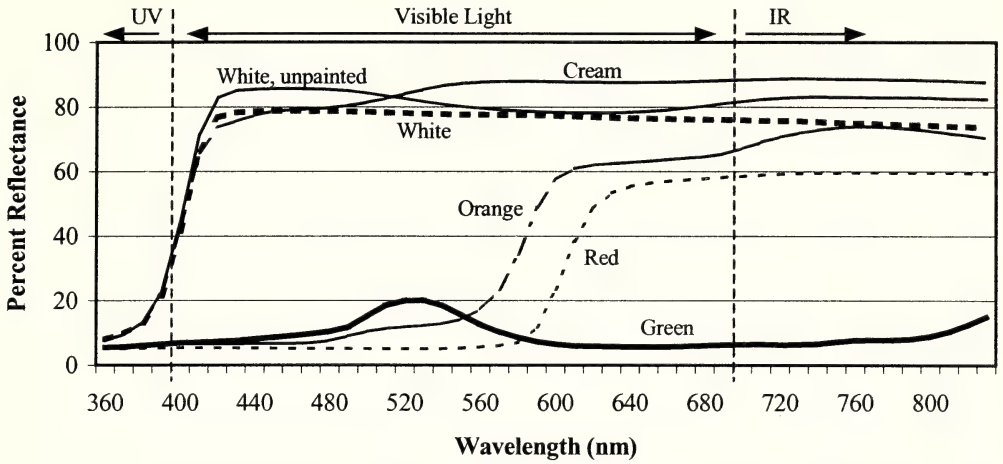

Figure 1. Percent reflectance from 360 to 830 nm of six corrugated plastic delta-shaped traps either left unpainted (white) or painted cream, red, green or orange.

Significant differences were found in the mean capture of codling moths, honeybees and flies in all but one delta trap comparison in experiments 1 and 2 (Table 1). The fewest honeybees were caught in the red, orange, and green painted delta traps in experiment 1 and in the painted white, cream, red, and green traps in experiment 2. The painted white and cream traps caught significantly fewer honeybees than the unpainted white trap in experiment 1. All but the unpainted white trap caught significantly fewer honeybees than the orange trap in experiment 2.

The vast majority of flies caught during experiments 1 and 2 were the lesser stable fly, *Muscina stabulans* (Fallen), and the little house fly, *Fannia canicularis* L., likely immigrating from the nearby dairy. Red traps caught significantly more flies than all other colours, and orange traps caught significantly more flies than the cream, white, and

Table 1.

The influence of trap colour on the capture of codling moths, honeybees, and flies in delta traps placed in an apple orchard in experiments 1 (28 April) and 2 (12 May).

	Mean (SE) catch per trap				
	Codling moth	Honeybees		Flies	
Painted trap colour	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Unpainted, white	7.7 (2.5)c	9.5 (1.2)a	4.4 (0.7)a	0.1 (0.1)c	4.9 (1.0)
White	6.0 (1.6)c	2.3 (0.5)b	0.6 (0.2)c	0.0 (0.0)c	11.3 (4.5)
Cream	14.2 (3.6)bc	2.8 (0.4)b	0.9 (0.5)c	0.3 (0.2)c	5.9 (2.6)
Red	14.8 (3.5)abc	0.0 (0.0)c	0.0 (0.0)c	3.7 (0.7)a	23.3 (5.2)
Orange	29.8 (7.8)ab	0.3 (0.2)c	2.4 (0.7)b	1.8 (0.6)b	10.1 (1.6)
Green	34.9 (11.5)a	0.1 (0.1)c	0.0 (0.0)c	1.0 (0.3)bc	8.4 (1.8)
Statistical analysis	$F = 4.24$	$F = 42.11$	$F = 15.69$	$F = 12.58$	$F = 1.26$
df = 5, 54	$P < 0.01$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.30$

Means within the same column followed by the same letter are not significantly different at $P < 0.05$ (LSD test).

unpainted traps in experiment 1. Fly captures were much higher and more variable during experiment 2, though no differences were significant (Table 1).

No codling moths were caught in the unbaited traps in experiment 1. Significant differences in the catch of codling moths in experiment 2 occurred among trap colours (Table 1). The lowest mean catches were in the unpainted and white traps but these were not significantly different from the cream and red traps. Catch was significantly higher in the orange versus the white or unpainted traps. Mean moth catch in the green traps was significantly greater than in the unpainted, white or cream traps.

The green delta trap caught significantly more codling moths than the unpainted white trap (F = 42.64; df = 1, 10; $P < 0.001$); mean (SE) = 13.7 (2.4) versus 6.3 (1.2), respectively) in experiment 3. No honeybees were caught in any trap in experiment 3, and the capture of flies was low, averaging < 0.2 per trap, so data were not analyzed.

DISCUSSION

Visual cues are known to be an important factor affecting the close range orientation of male codling moth to females or synthetic lures (Castrovillo and Cardé 1980). Visual cues may also play a role in oviposition behaviour, which occurs from late afternoon to dusk (Riedl and Loher 1980). The role of colour on the orientation of male codling moths at dusk to discrete sex pheromone sources is unknown. The correlation of our traps' reflectance data and their relative capture of codling moth suggest that traps with low reflectance at wavelengths < 560 nm may catch more moths than the standard white and cream traps. A spectral analysis of the sensitivity of codling moth's compound eye may allow us to make a significant improvement in the design of a more effective monitoring trap.

It is not clear from the literature whether visual detection of a trap by a moth should increase or decrease the number of individuals captured in a sex pheromone-baited trap. For example, the compound eyes of some noctuid moths have been shown to have a bimodal sensitivity to light with peaks in the UV (350 – 370 nm) and green (500 – 575 nm) regions (Agee 1973, Mitchell *et al.* 1989). Yet, other noctuid species respond more strongly to traps emitting low spectral reflectance in these regions (McLaughlin *et al.* 1975).

The significant differences found in the effectiveness of delta traps of different colours in the capture of codling moths suggest that the potential influence of colour in previous codling moth trapping studies should be reexamined. Most of the paper and plastic traps used to monitor codling moth have been cream or white (Riedl *et al.* 1986). No studies with codling moth have compared traps of similar geometry that differ only in colour. Plastic bucket traps with a green flat top and a white cylindrical bottom were found to have higher seasonal catches of codling moth than paper, cream colour wing traps (Vincent *et al.* 1990). Knodel and Agnello (1990) found that a small, orange delta trap caught nearly twice as many codling moths as either the cream colour or white wing traps in their study. Conversely, they also reported that the all-green bucket trap caught fewer moths than any other design including two designs of a green and white bucket trap. However, these differences among the bucket traps could have been due to the significant differences in the size and geometry of the various traps' openings.

Green delta traps in our studies appeared to be the most selective and attractive colour for monitoring codling moth. Painted or unpainted white traps and cream traps all caught honeybees. We did not determine if red, orange or green traps differ in their attractiveness for codling moth. However, green and red appeared to catch somewhat fewer honeybees than orange traps, and both green and orange caught fewer flies than red traps.

The benefit derived by excluding honeybees from codling moth traps could be cancelled by an increase in the trap's captures of large flies in some orchards. The capture

of flies varied widely among our experiments due to differences in location and seasonality. The highest numbers of flies were caught in experiment 2 in an orchard situated near a dairy, and only negligible captures of flies occurred in experiment 3 in an orchard surrounded by other orchards. The higher counts of flies in experiment 2 versus experiment 1 were likely due to an increase in the mean maximum temperatures (> 3 °C) that occurred from late April to early May.

Visual stimuli are well known to be important factors affecting the behaviour of muscoid flies (McCann and Arnett 1972). The influence of colour on the level of attractiveness to the stable fly, *Stomoxys calcitrans* L., has been shown to be red > green > yellow > white (Muniz and Hecht 1968). The behavioural responses of *S. calcitrans*; the face fly, *Musca autumnalis* De Geer; and the horn fly, *Haematobia irritans* L., are all greatest to surfaces with < 20% reflectance in the range from 350 to 450 nm (Agee and Patterson 1983). Similarly, in our study the low captures of muscoid flies in the white and cream traps may be associated with their high mean reflectance (> 50%) in the range from 360 – 450 nm (Fig. 1). Thus it might be possible to reduce the capture of muscoid flies in the green, red, and orange traps if a UV reflector was added to the trap's surface.

The congregation of muscoid flies to surfaces can also be their response to regulate their body temperature (Bushman and Patterson 1981). Flies may congregate on warmer surfaces during cool mornings or afternoons (Agee and Patterson 1983). The interior surface of the darker delta traps during the summer can be 2 – 4% warmer than white traps (unpublished data). Further research detailing the influence of temperature and other climatic factors on the capture of muscoid flies in delta traps may allow us to further improve the selectivity of this trap in monitoring codling moth. Further studies on the visual sensitivity of codling moth and its associated behaviour may allow us to develop a trap that is both more attractive for codling moth and less attractive to muscoid flies.

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Testing an attracticide hollow fibre formulation for control of Codling Moth, *Cydia pomonella* (Lepidoptera: Tortricidae)

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ABSTRACT

Laboratory and field tests were conducted to evaluate the use of an experimental sprayable formulation of chopped hollow fibres loaded with codlemone and mixed with 1.0% esfenvalerate and an adhesive to control codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). Moths were not repelled by the addition of the insecticide to the adhesive and were rapidly killed following brief contact. A significantly greater proportion of male moths flew upwind and contacted individual fibres for a longer period of time when fibres had been aged $\geq$ 7 d versus fibres 0 – 7 days-old in flight tunnel tests. Field tests using sentinel fibres placed in 10.0 mg drops of adhesive on plastic disks stapled to the tree found that fibres were not touched until they had aged > 8 d. Conversely, moth mortality following a 3-s exposure to field-collected fibres deposited on the top of leaves was low in bioassays with fibres aged > 8 d. The deposition and adhesion of fibres within the apple canopy appear to be two major factors influencing the success of this approach. Fibres were found adhering to foliage, fruit, and bark within the orchard; however, visual recovery of fibres following each of the three applications was < 5.0%. Both the substrate and the positioning of the fibre on the substrate influenced fibre retention. The highest proportion of fibres was found initially on the upper surface of leaves and this position also had the highest level of fibre retention. Fibres on the underside of leaves or partially hanging off of a substrate were dislodged within two weeks.

Key words: sex pheromone, codling moth, attracticide, apple

INTRODUCTION

A variety of approaches have been developed that utilize the sex pheromone of codling moth, *Cydia pomonella* L., for its effective management in deciduous tree fruit and nut crops, including the application of hand applied dispensers (Charmillot and Pasquier 1992), sprayable microencapsulated materials (Charmillot and Pasquier 2001), widely-spaced aerosol emitters (Shorey and Gebers 1996), and paste droplets formulated with insecticides (Charmillot *et al.* 2000). Chopped hollow fibres loaded with codlemone have been used for codling moth both in hand-applied formulations (Cardé *et al.* 1977) and in a sprayable formulation in which the fibres were mixed with an adhesive (Moffitt and Westigard 1984). Fibres provided high levels of disruption throughout the season in these studies.

Hollow fibres have been widely used in aerial applications in cotton for management of pink bollworm, *Pectinophora gossyptella* (Saunders) (Baker *et al.* 1990). Cotton growers combined the use of the hollow fibres and synthetic pyrethroids to develop an attracticide formulation (Beasley and Henneberry 1984). Studies with pink bollworm showed that this attracticide approach had minimal effect on natural enemies (Butler and Las 1983) and had significant lethal and sublethal effects, which reduced the pest population (Floyd and

Crowder 1981). This attracticide approach has not been tested with codling moth. Herein are presented preliminary studies that evaluated the potential of this approach and the use of chopped fibres for communication disruption of codling moth.

MATERIALS AND METHODS

Laboratory test protocol. The response of male codling moths to an experimental formulation of black hollow Celcon fibres (200 μm i.d. x 15 mm) loaded with 15% codlemone diluted in hexane (Scentry Inc., Buckeye, AZ) was observed in a flight tunnel. Fibres were formulated to release 0.1 μg/h codlemone at 20 °C (Weatherston *et al.* 1985). The tunnel was 1.65 m long, 0.56 m wide and 0.56 m high and constructed from 6 mm thick acrylic sheeting. A blower was used to push air within the room (maintained at 22 – 24 °C and 50 – 60% RH) into a plenum, through a charcoal filter, and through a series of screens before passing into the working section of the tunnel. An identical blower was used on the opposite end to pull air through the tunnel. Power to the blowers was provided by two 12-volt battery chargers attached to 115-volt AC variable resistors. By carefully adjusting the speed of each blower, laminar airflow was created which passed through the tunnel at the rate of 0.13 m/sec (measured by movement of smoke). Exhaust was expelled to the outside of the building. Red lights installed above the working section of the tunnel provided enough light (4.3 lux) to make observations.

Insects were obtained as mature larvae inside corrugated cardboard strips from a laboratory colony reared on a soybean diet at the Yakima USDA Insectary (Toba and Howell 1991). Virgin male moths were collected daily and conditioned in constant light for 24 – 48 h at 21 °C and 60% RH. Prior to testing, moths were placed in complete darkness for 30 min.

Technical esfenvalerate (Dupont Agricultural Products, Wilmington, DE) was diluted in acetone and mixed with adhesive at a 1.0% wt/wt concentration. A single hollow fibre was placed on a 10.0 mg droplet of a polybutene adhesive (Biotac 100, Scentry Biologicals, Billings, MT) in the center of an 18.0 mm diameter plastic disk. The plastic disk with the fibre was placed on a small metal platform suspended 30 cm from the top of the flight tunnel at the air inlet end. Moths were released from a 30 cm high platform placed near the air outlet end of the tunnel. The number and duration of individual visits to the fibre were recorded for 7 min with an infrared motion detector coupled to a computer.

Attractiveness and toxicity of laboratory-aged fibers. Two types of tests were conducted in the flight tunnel to assess the attractiveness of individual fibres for male codling moths and the toxicity and possible repellency of adding an insecticide to the adhesive. In the first test, hollow fibres were aged for 7 d at 24 °C prior to testing. Ten replicates of 10 moths were flown to a fibre placed either in adhesive or in adhesive with insecticide. Treatments were run alternately for each replicate, n = 10. The attractiveness and toxicity of fibres placed on adhesive treated with 1.0% esfenvalerate and aged in a greenhouse were evaluated in the second test. Disks were collected after 0, 1, 4, 7, 14, 21, and 28 d and kept frozen at –10 °C. Five fibres from each age class were tested in the flight tunnel in a random order and each fibre was tested twice, n = 10 replicates. Six males were released simultaneously for each fibre and allowed to fly for 7 min. Moths were collected individually in vials at the end of each flight test and mortality was scored after 24 h at 24 °C.

Field test protocol. Field studies of fibres were conducted in 1992 and 2003. Three applications of fibres were made to a 0.3 ha (214 trees) 5-year-old 'Golden Delicious' block trained on a M-16 rootstock with central leader architecture on 5 May, 1 June, and 28 July 1992. The mean (SE) height of trees was 2.1 (0.1) m. A standard spinning cone

applicator used for ground application of the fibre in field crops (Moffitt and Short 1982) was supplied by Scentry personnel and attached to a tractor. The tractor and sprayer were calibrated to deliver 100.0 g of fibres (15.0 g a.i.) in 6.0 L adhesive per hectare. The deposition and retention of fibres were evaluated following an application on 9 July 2003 in a 4.0-ha orchard of mixed apple cultivars. The orchard was treated with 250.0 g of a 10.0% a.i. fibre mixed with 4.7 L adhesive per hectare using a specialized tractor-pulled overhead applicator (Blue Line Manufacturing, Wenatchee, WA). The same adhesive and fibre were used in both years.

Attractiveness and toxicity of field-aged fibres. The attractiveness and toxicity of field-aged fibres were evaluated throughout the 1992 season. On each of the three spray dates one fibre was placed on a 10.0 mg adhesive drop in the center of each of 120 plastic disks that were stapled to the wooden posts of a wire deer fence situated > 50 m from the apple orchard. On each subsequent sampling date 10 disks without any moth scales were placed in the upper third of the apple orchard's canopy in a horizontal position. These sentinel fibres were left in the orchard for 5 – 7 d and then reexamined with a microscope for the presence of moth scales. In addition, on each sampling date 10 fibres deposited by the spray application on the upper surface of leaves were collected from the orchard and returned to the laboratory. Five 1 – 2 d-old chilled laboratory-reared moths were touched to each fibre using a suction hose for 3 s. Moth mortality was scored after 24 h at 24 °C.

Deposition and retention of fibres. Several studies were conducted during the season to assess the deposition and retention of fibres in the apple orchard. A trial was conducted on 12 September to estimate the number of fibres applied per hectare. Blank white celcon fibres (200 μm i.d. x 15 mm) were mixed with the adhesive and applied at the standard rate (100.0 g in 6.0 liters adhesive). Five dark blue tarps (2.92 m x 2.92 m) were placed in a row on a grassy strip. The sprayer was started 50 m away from the first tarp and once fibres had begun to be released from the spinning cone the tractor was driven forward at a speed of 4.0 km per h. The number of fibres deposited on each sheet was counted and used to estimate the number of fibres applied to the entire orchard (area equivalent to 426 tarps). Deposition of fibres within the canopy of the orchard was estimated following each spray application by visually examining 60 trees for fibres. Individual trees were inspected for 3 to 5 minutes from the ground. The retention of marked fibres within the canopy of the apple orchard was evaluated following the June application in 1992. Fifty-seven fibres were located on leaves and their location was marked with flagging. The retention of these fibres was checked after 2 and 7 wk.

One hundred and twenty-two fibres were located and marked with flagging one day after the application in 2003. The position of each fibre was recorded with respect to substrate and whether the fibre was in full contact with the substrate or if a portion of the fibre was detached from the substrate (overhanging). Their retention in the canopy was subsequently evaluated on 14 and 21 July and 22 August.

Statistical analyses. An unpaired t-test and analysis of variance on transformed data (square root [x+0.01]) were used to compare the attractiveness and toxicity of fibres placed in adhesive either with or without insecticide and to fibres aged from 0 – 28 d to cohorts of moths, respectively (Analytical Software 2000). Means in significant ANOVA's were separated with Fisher's LSD test, $P < 0.05$.

RESULTS

Attractiveness and toxicity of laboratory-aged fibers. No difference was found in the number of moth visits to fibres placed in either clean (mean ± SE = 13.4 ± 1.7) or insecticide-impregnated (17.4 ± 2.3) adhesive during the 7-minute bioassay in the flight tunnel ($t = 1.40$, df = 18, $P = 0.18$). Similarly, no difference was found in the duration of a moth visit between fibres placed in clean (1.9 ± 0.5) or insecticide-impregnated adhesive

(1.8 ± 0.4) (t = -0.09, df = 18, P = 0.93). Subsequent tests showed that the age of the fibre was a significant factor affecting moth contact and moth mortality (Table 1). Fibres placed in insecticide-impregnated adhesive and aged for < 7 d had significantly fewer moth contacts and reduced visitation time. No difference in either factor was found for fibres aged 14 – 28 d. A significantly greater proportion of moths per cohort were killed when flown to fibres aged 14 - 28 d versus < 1 d-old fibres. The highest moth mortality occurred with fibres aged 14 d (Table 1). The lack of a significant difference in moth mortality following exposure to fibres aged 4 – 7 d versus 21 – 28 d may have been due to a decline in the toxicity of the insecticide in the older drops.

Table 1

Influence of age on the attractiveness and toxicity of an individual hollow fibre loaded with 15% codlemone and placed on a 10.0 mg drop of adhesive treated with 1.0% esfenvalerate for male codling moths flown in a flight tunnel.

Age of fibre (d)[a]	Mean (SE) # of contacts[b]	Mean (SE) time (s) per source contact[b]	Mean (SE) proportion of dead moths[c]
0	2.4 (0.9) c	0.3 (2.1) b	0.29 (0.04)c
1	1.4 (0.7) c	0.2 (0.1) b	0.20 (0.05) c
4	1.9 (1.0) c	0.1 (0.03) b	0.50 (0.09) bc
7	5.7 (1.4) bc	0.3 (0.1) b	0.49 (0.05)bc
14	16.8 (3.5) a	1.4 (0.3) a	0.88 (0.04)a
21	11.8 (2.6) ab	0.9 (0.2) ab	0.68 (0.12) ab
28	19.1 (5.8) a	1.4 (0.5) a	0.67 (0.10) ab
Statistical analysis	F = 6.82; df = 6, 63; P < 0.0001	F = 3.93; df = 6, 46; P < 0.01	F = 9.82; df = 6, 46; P < 0.001

[a] Fibres were aged in a greenhouse maintained between 20 – 24 °C for up to 28 days.
[b] Ten cohorts of six moths were flown in the flight tunnel for 7 minutes for each fibre age class. The mean number of moth contacts and time per source visit per cohort were measured with an infrared motion detector hooked to a computer.
[c] Following each tests moths which contacted adhesive were collected and placed individually in vials. Mortality was scored after 24 h at 24 °C.

Attractiveness and toxicity of field-aged fibres. No moth scales were found on the sentinel fibres placed in the apple orchard during the first eight days after any of the three applications (Table 2). The proportion of fibres aged from 8 – 51 d visited by moths ranged from 0.43 – 0.85 during the season. Mortality of moths in the 3-s touch bioassay was > 85% for fibres collected on the day of the spray application. In general, fibres were initially sticky and associated with several milligrams of adhesive. Moth mortality dropped sharply with field aging of the fibres, however, 65 – 80% mortality occurred with 8 d and 5 d old fibres after the second and first applications, respectively. Moth mortality was much lower with 7 d-old fibres following the third application (Table 2). Moth mortality with field-collected fibres collected 2 – 7 wk after the application ranged from 0.0 – 30.0%.

Deposition and retention of fibres. The mean (SE) number of fibres counted per tarp was 32.9 (15.3). Extrapolating the deposition of fibres on the tarps to the area of the entire orchard (equivalent to 426 tarps) estimated 14,015 fibres were applied. Following the 5 May spray application a mean (SE) of 0.9 (0.3) fibres were sampled per tree. This first application was made a few days past full bloom and the growth of green foliage was limited. The mean density of fibres following the 1 June application when trees had abundant foliage increased to 2.5 (0.4) fibres per tree. However, fibre density following the

third application on 28 July was somewhat lower, 1.5 (0.4) fibres per tree. The highest density of fibres found on a single tree during the season was 17. Extrapolating the mean density of fibres sampled per tree (1.5 – 2.5) multiplied by the number of trees in the block (214) suggests that only 2.3 – 3.8% of the estimated number of fibres sprayed in the orchard (14,015) were deposited on the trees.

Table 2

Proportion of sentinel hollow fibres placed in 10 mg adhesive on a plastic disk at various times following a spray application that contained moth scales and moth mortality following a 3-s touch to field-aged fibres deposited on the upper surface of apple leaves.

Date checked	Post-spray interval (d) fibre was in field	Proportion of fibres touched [a]	% moth mortality in touch bioassay [b]
5 May	0	--	100.0
10 May	1 - 5	0.00	80.0
17 May	5 - 12	0.85	22.0
1 June	0	--	96.0
9 June	2 - 8	0.00	65.0
16 June	8 - 15	0.45	30.0
23 June	15 - 22	0.85	10.0
30 June	22 - 29	0.60	12.0
7 July	29 - 36	0.40	18.0
14 July	36 - 43	0.55	6.0
22 July	43 - 51	0.40	0.0
28 July	0	--	86.0
4 August	1 - 7	0.00	26.0
11 August	7 - 14	0.75	14.0
19 August	14 - 22	0.43	8.0

[a] Positive visitation of codling moth to sentinel fibres was based on the microscopic detection of moth scales in the adhesive surrounding each sentinel fibre. Fibres and adhesive were placed in the center of plastic disks that were stapled horizontally in the upper third of the tree canopy and left in the field for 5 – 7 d.

[b] Moth mortality was assessed 24 h following a 3 s touch exposure to a field-collected fibre on the upper surface of a leaf. Five moths were tested per fibre and ten fibres were collected on each date.

Table 3

Retention of hollow fibres loaded with codlemone and mixed with an adhesive in the canopy of an apple orchard following a spray application on 9 July 2003.

Position of fibre	# fibres	% fibres lost after		
		4 d	11 d	43 d
Top of leaf	52	9.6	17.3	25.0
Top of leaf, overhanging	19	36.8	84.2	100.0
Bottom of leaf	9	55.6	55.6	100.0
Bottom of leaf, overhanging	16	68.8	75.0	100.0
Fruit	21	28.6	47.6	61.9
Bark	5	20.0	40.0	80.0
Total	122	28.7	49.2	59.8

Retention of fibres on apple trees was short-lived. Following the 1 June application in 1992, < 50% of marked fibres on leaves were retained on trees after 2 wk and approximately 10% were retained after 7 wk. The 2003 study showed that the retention of fibres is variable based on differences in their location and alignment on various substrates (Table 3). Following the 9 July application 58% of fibres were located on the top of leaves. Deposition of fibres on the bottom of leaves and on fruit was similar with about 20% each. Fibres deposited on the trunk and branches of trees accounted for < 5% of the total. A large proportion of fibres deposited initially on leaves were found overhanging the edge of the leaf. This was more common for fibres deposited on the underside of leaves with 64% of fibres overhanging. Retention of fibres was highest on the top of leaves with fruit being the second best. Fibres overhanging on leaves and all fibres deposited on the underside of leaves were lost within 43 d. In comparison, 60% and 80% of the fibres deposited on fruit and bark were loss within 6 wk, respectively. Only a quarter of the fibres deposited on the top of leaves and not overhanging were lost.

DISCUSSION

The experimental formulation of hollow fibres loaded with codlemone and mixed with an insecticide in this study was ineffective as an attracticide due to several factors including the emission rate of the fibre and the toxicity of the adhesive. The initial emission rate of codlemone from individual fibres was apparently too high to allow moth contact. Fibres had to be aged for > 7 d before male codling moths would contact fibres under both flight tunnel and field conditions. Moth mortality was high following brief contact with newly applied fibres but dropped rapidly with time. Modifications are needed to improve the performance of this attracticide approach.

The emission characteristics of sex pheromones from hollow fibres are well studied (Ashare *et al.* 1982). Fibres typically have an initial high release and then have a lower and fairly constant rate over an extended period of time. Previous studies with hollow fibres loaded with codlemone have shown that fibres can be long lived. Cardé *et al.* (1977) reported complete shutdown of lure-baited traps for 10 wk. Moffitt and Westigard (1984) reapplied fibres every 4 – 5 wk during the season. The emission rate of hollow fibres can be adjusted by modifying either the internal diameter of the fibre or by changing the length of the fibre (Ashare *et al.* 1982). Modifications of these factors could likely improve the use of fibres as an attracticide for codling moth.

Proper choice of an adhesive is critical in developing an effective attracticide. The viscosity of the adhesive affects both the application and the adhesion of the fibres. The polybutene adhesive Biotac has been widely used with hollow fibres (Beasley and Henneberry 1984, Moffitt and Westigard 1984) and is available in several formulations that differ in their viscosity and are appropriate for the range of temperatures experienced from early spring to late summer. Yet, fibres were generally associated with limited amounts of adhesive, < 1.0 mg; and were often poorly attached to the plant. In contrast, the initial laboratory studies placed fibres on large 10.0 mg drops of adhesive. This limited amount of adhesive associated with fibres under field conditions formed a dry film that was not effective in transferring a toxic dose of insecticide to codling moth adults. In comparison, the large drop of Biotac was toxic for several weeks in laboratory bioassays. The use of non-drying grease or a different type of adhesive instead of Biotac might extend the toxicity of the insecticide under field conditions.

Future improvements of the attracticide method for codling moth could include the use of a more concentrated insecticide dose. A 1.0% sticker formulation with permethrin and fenvalerate did not cause mortality of *P. gossypiella* while a 10.0% concentration was effective (Haynes and Baker 1986). Yet, formulations with only 0.1% concentrations of cyfluthrin killed 100% of codling moths when formulated in a castor oil-based paste (Lösel

et al. 2000). One attract and kill paste formulation currently registered for control of codling moth contains 6.0% permethrin (Charmillot *et al.* 2000). These paste formulations remain effective against codling moth for at least 6 wk (Charmillot *et al.* 2000, Lösel et al 2000).

The impacts of an attracticide approach can include both lethal and sublethal effects such as the interference with mate location by males (Haynes and Baker 1986). While sublethal effects were not examined in our field studies, previous flight tunnel tests with codling moth found significant effects on male flight behaviours with concentrations of esfenvalerate as low as 0.04% (unpublished data). Further studies that can characterize the sublethal effects of the range of attracticide formulations for codling moth would be useful.

Depositing more fibres in the canopy would improve the effectiveness of this formulation both as an attracticide and for mating disruption of codling moth. The application methods used to apply fibres have included specialized and expensive ground and air equipment (Moffitt and Short 1982). Results reported here suggest that this approach is ineffective in placing a significant number of hollow fibres in the tree canopy. Fibres deposited in the apple tree canopy were primarily deposited in the middle of the upper leaf surface. This fibre position also appeared to be the most stable over time with nearly 75% of fibres retained after 6 wk. Unfortunately, the adhesion of fibres to bark or the underside of leaves was low and short-lived. Increasing the number of fibres sprayed per hectare is one approach that could be used to increase the density of deposited fibres. Ground applications in orchards with larger trees or denser canopies or perhaps the use of aerial applications might improve the deposition rates of hollow fibres and needs to be further examined.

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Numbers and types of arthropods overwintering on common mullein, *Verbascum thapsus* L. (Scrophulariaceae), in a central Washington fruit-growing region

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ABSTRACT

Densities and types of arthropods overwintering on common mullein, *Verbascum thapsus* L., in a fruit-growing region of Central Washington were determined. Over 45,000 arthropods were collected from 55 plants (5 plants from each of 11 sites), dominated numerically by Acari and Thysanoptera. Insects representing 8 orders and 29 families were identified, distributed both in the basal leaf rosettes and in the stalk material of the plants. One specialist insect herbivore of mullein, the mullein thrips, *Haplothrips verbasci* (Osborn), was abundant at all sites. Several pest and predatory taxa that commonly occur in orchards were also collected, suggesting that mullein may be a source of overwintered pests or predators moving into orchards in early spring. Pest taxa included primarily western flower thrips (*Frankliniella occidentalis* (Pergande)), *Lygus* spp., and tetranychid spider mites. Common predators included phytoseiid mites and minute pirate bugs (*Orius tristicolor* (White)). Sites that were geographically close to one another were not more similar (in taxonomic composition of overwintering arthropods) than more distantly separated sites.

Key words: common mullein, overwintering, orchard pests, predatory arthropods, mullein thrips, western flower thrips, *Orius tristicolor*, mites

INTRODUCTION

Common mullein, *Verbascum thapsus* L. (Scrophulariaceae), is a biennial herb native to Eurasia (Munz 1959) but now common throughout North America. The species occurs in open waste areas, along fence lines, in overgrazed pastures, and along river bottoms, often found growing in large single-species stands. Common mullein has a biennial life cycle, germinating from seed often near clumps of the dead parental plants. In the first year, the plant develops as a rosette of soft, bluish-gray leaves which are densely covered with silky hairs. The following year, a stout, leafy stalk is sent up from the center of the rosette, often reaching a height of more than 2 m in mid-summer. At the top of the stalk is a spike having 100-200 yellow flowers which are in bloom several at a time for much of the summer.

There is a great deal of interest in managing or conserving non-agricultural habitats adjacent to agricultural habitats to enhance biological control or to reduce infestation of crops by pest species (Pickett and Bugg 1998; Ekbom *et al.* 2000). In Pacific Northwest fruit growing regions, common mullein often is abundant on the perimeter of pome and stonefruit orchards. The plant is known to harbor important pests of tree fruits during the growing season (Thistlewood et al. 1990; Krupke et al. 2001), but it also is an important source of certain predators (e.g., *Campylomma verbasci* (Meyer), the mullein bug) that may provide biological control of aphids and mites during the growing season. Less information is available concerning use of mullein by pests and predators as an overwintering habitat (McAtee 1924). It is important to understand late winter and early spring population dynamics of pests and predators in pear and apple orchards, as that time of year is often crucial for pest control. Thus, we need also to understand the overwintering biology of arthropods both inside and outside of the orchard, including a determination of where pests and predators overwinter

(Horton and Lewis 2000; Horton *et al.* 2002).

McAtee (1924), in Maryland, conducted a cursory survey of the insects associating with common mullein, and found that the dense basal rosette of leaves provided overwintering habitat for several taxa of arthropods, including both pest and predatory insects. Thus, in addition to being a source of pest and beneficial arthropods during the summer and fall growing season, common mullein may also be a source of overwintered arthropods moving into Central Washington orchards in late winter and early spring. Objectives of the present study were to determine types and densities of arthropods overwintering on common mullein in a fruit-growing region of Central Washington. The study was designed to provide a more thorough look at the arthropod communities in mullein than provided by McAtee (1924), and to provide data for a western US population of mullein. We also compared types and numbers of arthropods overwintering in the basal rosette of leaves to numbers and types occurring in the leaves, dried flowers, and seed capsules of the stalk. Lastly, we looked for geographic patterns in the taxonomic composition of arthropod communities overwintering in mullein, testing the hypothesis that arthropod communities would be more similar between sites that occur geographically near one another than between sites that were more widely separated.

MATERIALS AND METHODS

The study was done in and adjacent to Yakima, Washington, USA. Eleven sites, each having stands of fully mature common mullein, were selected in November 2000 for sampling. Plants that were sampled had bloomed the previous summer and were composed of dead leaves and seed-laden stalks at the time of collection. All of the sites were along roadsides that occurred immediately adjacent to orchard habitat or within 1 km of orchard habitat. Straight-line distances between sites ranged between 0.5 to 46.4 km. In December 2000 and January 2001, we collected five fully mature plants (1.5 to 1.8 m tall) from each site by cutting the plants just beneath the soil surface. Plants were placed in large plastic bags for transport to the laboratory. Bags and plants were placed in a large walk-in cooler (2 °C) until the arthropods were extracted. To extract the arthropods, the plant material was distributed among 25 Berlese-Tullgren funnels (Southwood 1980), keeping stalks and leaf rosettes separate. We used 40 watt light bulbs to force the arthropods into 75% ethanol.

Arthropods were then separated from the plant detritus by first slowly pouring the alcohol through very fine (0.2 x 0.2 mm) organdy mesh. The mesh appeared to capture all but the very smallest mites (mostly immature Tydeidae and Tenuipalpidae). These specimens were discarded without being identified, thus summaries provided below for Acari underestimate total numbers of certain small-bodied taxa. The arthropods remaining on the mesh were removed from the mesh and plant detritus with forceps, insect pins, or small paint brushes, and transferred to fresh 75% ethanol for later counting and identification.

Insects other than Lepidoptera (all of which were in the caterpillar stage) and parasitic Hymenoptera were identified at least to family. Known important predators and pests in orchards were identified to species. Most samples contained very large numbers of Thysanoptera, and it was not feasible to identify each specimen. A subsample of 50 thrips was removed from each sample for identification to genus beneath a dissection microscope, using the key of Mound and Kibby (1998). Immature thrips were not classified. Results for the subsample were then extrapolated back to the full sample to provide estimates of total numbers of thrips for each genus. Representative examples of each genus were sent to an expert in thrips identification (Steve Nakahara; Beltsville, MD) to confirm our identifications.

Mites were very abundant in the leaf rosettes and much less abundant in the stalk material, thus we limited acarine identifications to those mites inhabiting the leaf rosettes. The identifications were confined to six of the 11 sites. We first separated Gamasida from the total sample, for later examination. From the remaining sample, a subsample of approximately 50

to 500 mites (depending upon total numbers in the sample) were mounted in Hoyer's solution on microscope slides (Krantz 1978). The mites were then identified to genus (*Tetranychus* spp. only) or to family under a compound microscope using keys in Krantz (1978). Counts for *Tetranychus* spp. were then extrapolated back to the total sample to obtain estimates of absolute densities for *Tetranychus* spp. From the Gamasida whole sample, subsamples of 25 to 85 mites were then taken for those sites having large numbers of gamasid mites (>90 mites). The mites were mounted on slides in Hoyer's solution and identified to family (all but Phytoseiidae) or to species (Phytoseiidae). Species identifications for the Phytoseiidae were made using keys in Schuster and Pritchard (1963) and Chant *et al.* (1974). We then extrapolated results for the subsample back to the full Gamasida sample to provide estimates of absolute numbers for phytoseiid species.

Straight-line distances between sites were obtained using a Vista global positioning unit (Garmin; Olate, KS). We tested whether sites that were geographically near one another were more similar than those more distantly separated by calculating taxonomic (family-level) similarity between all possible site pairs, using the following formula:

$$\text{Relative absolute distance} = \sum_i \text{Absolute value } [(x_{ij}/\sum_i x_{ij}) - (x_{ik}/\sum_i x_{ik})] ,$$

where j and k are two sites, x_{ij} is the abundance of the i^{th} insect family at site j, and x_{ik} is abundance of the i^{th} insect family at site k (Ludwig and Reynolds 1988). The analysis was limited to families of Insecta. The index varies between 0 and 2, with 0 indicating maximum similarity and 2 indicating complete dissimilarity between the two sites.

RESULTS

A total of 46,712 arthropods was counted from the 11 sites, of which 44.7% were collected from the leaf rosettes and the remaining 55.3% were collected from the stalk material. The samples were dominated numerically by the Thysanoptera and Acari (Table 1), accounting for over 90% of the arthropods from both leaf and stalk material. For the Insecta, 29 families in 8 orders were identified, with species of Thysanoptera, Coleoptera, and Heteroptera being the most abundant. There was considerable site-to-site variation in counts (Table 1, Range) for virtually all common taxa.

Mites were very abundant in the leaf rosettes (exceeding 500 per 5-plant sample) and much less abundant in the stalk material (Table 1). Specimens from leaf rosettes at six of the 11 sites were identified, and were found to include large numbers of Gamasida and Actinedida (Table 2). Gamasida were composed primarily of Phytoseiidae, including some important predatory species (*Amblyseius* spp.; *Typhlodromus caudiglans* Schuster; western predatory mite, *Galendromus occidentalis* (Nesbitt)). Spider mites (Tetranychidae) were relatively uncommon (Table 2), and included primarily *Tetranychus* spp. (47 of 64 tetranychids in subsamples).

Thysanoptera included two families, Thripidae and Phlaeothripidae (Table 1), the latter apparently being represented by a single species, *Haplothrips verbasci* (Osborn), the mullein thrips. This species was very abundant in both stalks and leaf rosettes, reaching densities of over 800 adults per stalk at one site. Thripidae included species of *Thrips* (apparently mostly *Thrips tabaci* Lindeman but including *T. fallaciosus* Nakahara), *Caliothrips*, and *Frankliniella* (apparently all western flower thrips, *F. occidentalis* (Pergande)).

Homoptera were composed primarily of aphids and psyllids (Table 1), including pear psylla, *Cacopsylla pyricola* (Foerster), a pest of pears. Heteroptera were dominated numerically by Anthocoridae and Miridae (Table 1). The 75 Tingidae that were collected all occurred in the leaf rosettes at a single site. Anthocoridae were almost exclusively minute pirate bug, *Orius tristicolor* (White) (164 total specimens), but included also five specimens of *Xylocoris umbrinus* Van Duzee. Overwintering Coleoptera were dominated numerically

Table 1

Mean (averaged over 11 sites) numbers of arthropods per 5 mullein plants in leaf rosettes and stalk material. Numbers in parentheses indicate percentage of total arthropods composed of that taxon [(tr) indicates less than 0.1%]. Range shows minima and maxima across the 11 sites. Family means may not sum to order means due to presence of unidentified arthropods in that order (particularly true for Thysanoptera, for which immatures were not identified).

	Leaf rosettes		Stalks	
	Mean numbers per 5 plants (%)	Range (per 5 plants)	Mean numbers per 5 plants (%)	Range (per 5 plants)
Acari	534.2 (28.1)	123-1455	34.0 (1.4)	3-167
Thysanoptera	1266.9 (66.7)	30-3936	2263.5 (96.5)	210-5516
Thripidae	515.6	0-2362	590.4	49-1655
Phlaeothripidae	710.6	25-1652	1467.5	64-4174
Homoptera	8.0 (0.4)	1-29	4.5 (0.2)	0-22
Aphididae	3.3	0-14	0.6	0-3
Cercopidae	0.1	0-1	0.0	0
Cicadellidae	0.3	0-1	0.0	0
Psyllidae	4.3	0-14	3.8	0-8
Heteroptera	30.5 (1.6)	4-87	8.9 (0.4)	0-32
Anthocoridae	7.5	0-22	7.7	0-30
Berytidae	0.1	0-1	0.0	0
Lygaeidae	1.6	0-16	0.0	0
Miridae	10.6	0-64	0.8	0-6
Nabidae	0.1	0-1	0.0	0
Pentatomidae	0.6	0-2	0.0	0
Reduviidae	0.1	0-1	0.0	0
Rhopalidae	2.3	0-12	0.1	0-1
Tingidae	6.8	0-75	0.0	0
Coleoptera	35.6 (1.9)	1-169	33.5 (1.4)	6-98
Anthicidae	0.0	0	0.1	0-1
Carabidae	0.2	0-1	0.0	0
Coccinellidae	0.5	0-1	0.0	0
Corylophidae	5.7	0-37	0.6	0-6
Curculionidae	27.5	1-130	32.5	6-98
Dermestidae	0.0	0	0.1	0-1
Staphylinidae	0.8	0-3	0.0	0
Neuroptera	0.5 (tr)	0-2	0.1 (tr)	0-1
Hemerobiidae	0.5	0-2	0.1	0-1
Lepidoptera	3.9 (0.2)	0-17	0.3 (tr)	0-2
Diptera	2.7 (0.1)	0-16	0.4 (tr)	0-2
Cecidomyiidae	1.5	0-11	0.2	0-2
Chironomidae	0.2	0-2	0.1	0-1
Mycetophilidae	0.1	0-1	0.0	0
Syrphidae	0.1	0-1	0.0	0
Hymenoptera	10.2 (0.5)	0-73	0.5 (tr)	0-2
Parasitoids	3.5	0-7	0.5	0-2
Formicidae	6.5	0-69	0.0	0
Vespidae	0.1	0-1	0.0	0
Araneae	7.4 (0.4)	0-21	0.8 (tr)	0-3
Opiliones	0.1 (tr)	0-1	0.0 (tr)	0
Chilopoda	0.2 (tr)	0-1	0.0 (tr)	0
Isopoda	0.1 (tr)	0-1	0.0 (tr)	0

Table 2

Taxonomic composition of mite subsamples (Oribatida, Acaridida, Actinedida) and absolute numbers of Gamasida in mullein leaf rosettes at each of 6 sites.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Oribatida	49	1	5	27	0	1
Acaridida	2	35	5	7	6	1
Actinedida	76	121	55	551	57	237
Anystidae	53	37	15	3	7	7
Bdellidae	2	14	0	0	0	0
Camerobiidae	10	4	4	0	4	17
Cunaxidae	0	0	1	7	0	0
Raphignathidae	3	21	11	0	1	0
Smarididae	2	11	0	0	0	0
Tarsonemidae	0	0	0	128	0	0
Tenuipalpidae	3	0	0	0	1	0
Tetranychidae	2	31	13	4	9	5
Tydeidae	1	3	11	409	1	208
Unidentified	0	0	0	0	34	0
Counted but not classified	0	235	90	841	92	364
Gamasida	238	94	58	29	52	379
Ameroseiidae	0*	0*	0	4	0	0*
Ascidae	1*	1*	38	2	0	0*
Laelapidae	0*	8*	7	0	0	0*
Phytoseiidae	83*	17*	13	23	51	81*
Unidentified	1*	1*	0	0	1	3*

* Results for a subsample of mites taken from the Gamasida total.

by an unidentified weevil that appears to be associated with the flowering and seeding mullein stalk also during the growing season. For the remaining taxa, spiders and ants were fairly abundant (both exceeding five specimens per 5-plant sample) in the leaf rosettes. Over 90% of the ants were collected at a single site.

Known tree fruit pests overwintering in mullein included pear psylla, spider mites, western flower thrips, *Lygus hesperus* Knight, and *Lygus elisus* Van Duzee (Table 3). Western flower thrips was especially abundant in the stalks, where densities reached 1000 thrips per 5- plant sample. *Lygus* spp. had a density of over 10 bugs per 5-plant sample overwintering in the leaf rosettes (Table 3). Beneficial arthropods known to occur in orchards and found overwintering in mullein included primarily phytoseiid mites and minute pirate bugs (Table 3), with much lower numbers of a few other species. Phytoseiidae included species of *Typhlodromus*, *G. occidentalis*, and unidentified *Amblyseius*. Minute pirate bugs were common, having a density of almost 15 bugs per 5-plant sample.

Taxonomic similarity (based upon insect families) between sites showed no relationship with distance between sites (Fig.1).

DISCUSSION

A large and diverse community of arthropods used both the leaf rosettes and stalks of common mullein as overwintering habitat. The communities were dominated numerically by Thysanoptera (leaves and stalks) and Acari (leaves), but other taxa including Heteroptera and Coleoptera were also relatively common. At certain sites, insects and mites overwintering in mullein easily exceeded a density of 1000 arthropods per plant, numbers considerably larger

Table 3

Mean densities (averaged over 11 or 6 [Acari] sites) of arthropods found overwintering in mullein that are also known pest or natural enemy inhabitants of orchards. Densities expressed as numbers per 5 mullein plants. Mites not identified for stalk samples.

		Leaf rosettes	Stalks
ORCHARD PESTS			
Acari	Tetranychidae	25.8	--
	Tetranychus (*urticae* group[1])	19.0	--
Thysanoptera	*Frankliniella occidentalis*[2]	280.0	733.4
Homoptera	*Cacopsylla pyricola*	3.5	3.6
Heteroptera	*Lygus* spp.	10.5	0.6
ORCHARD BENEFICIALS			
Acari	Phytoseiidae	124.0	--
	Galendromus occidentalis[3]	106.5	--
	Typhlodromus spp.[3]	11.3	--
	Amblyseius spp.[3]	6.2	--
Heteroptera	*Orius tristicolor*	7.2	7.7
	Deraeocoris brevis (Uhler)	0.1	0.2
	Geocoris spp.	0.6	0.0
Coleoptera	*Stethorus picipes* Casey	0.2	0.0

[1] Mean density estimated by extrapolating from subsamples (Table 2); spider mites were identified using keys in Baker and Tuttle 1994.

[2] Mean density estimated by extrapolating from subsamples.

[3] Mean density estimated by extrapolating from subsamples of Gamasida (Table 2).

than those reported by McAtee (1924) in Maryland (who appears to have ignored Acari and Thysanoptera in his brief study). It is of interest that a plant native to Eurasia would host such substantial numbers of phytophagous arthropods in North America. However, several of the most common species that we collected are cosmopolitan or Holarctic in distribution, including western flower thrips and mullein thrips, and it is likely that these species have geographic ranges in Europe and Asia that overlap the native range of common mullein. Indeed, the mullein thrips is known to specialize on species of *Verbascum* in Europe and North America (Bailey 1939). Bailey records this thrips as overwintering both in the leaf rosette and in the seed capsules or stalk material of *V. thapsus*, as shown also here.

The western flower thrips was very abundant overwintering in mullein (Table 3), suggesting that this plant may be an important source of flower thrips moving into orchards during early spring. Western flower thrips is a major source of early season damage on nectarines and certain apple varieties in the Pacific Northwest (Madsen and Jack 1966; Bradley and Mayer 1994; Pearsall and Myers 2000). Pearsall and Myers (2000, 2001) concluded that location of nectarine orchards in relation to wild habitats strongly affected early-season densities of thrips in orchards, with those orchards adjacent to other orchards (rather than adjacent to non-orchard habitats) having the lowest spring densities of thrips. These authors suggested that certain herbaceous and shrubby plant species in native habitats of the Pacific Northwest are a source of flower thrips that colonize nectarine orchards. Pearsall and Myers (2000) did not include common mullein in their list of important plant species, but results reported here indicate that common mullein should also be considered to be an important source of western flower thrips in tree fruit growing regions of the Pacific Northwest.

Other potential pests of tree fruits, including pear psylla, *Lygus* spp., and spider mites,

were present in mullein but at considerably lower densities than flower thrips. Pear psylla is known to overwinter in a variety of locations outside of the pear orchard (Kaloostian 1970). *Lygus* spp. are sporadic pests in pear, apple, and stone fruit crops (Beers *et al.* 1993). Common mullein has been reported to be a host plant of *Lygus lineolaris* (Palisot de Beauvois) in eastern North America (Young 1986), but it is not clear whether the two species recovered in the present study (*L. hesperus* and *L. elisus*) use mullein as more than overwintering habitat. McAtee (1924) recorded that *Lygus* sp. overwintered on common mullein leaf rosettes in Maryland. Spider mites are often abundant on broad-leaf plants within and adjacent to orchards, and these plants appear to be sources of pest mites moving into fruit trees during the summer (Flexner *et al.* 1991; Alston 1994; Coli *et al.* 1994). Our results indicate that common mullein growing near orchards in the Pacific Northwest may be a source of overwintered spider mites that could eventually disperse into fruit trees.

Several important predator species also overwintered on common mullein, including the highly abundant *O. tristicolor* and predatory mites. *Orius tristicolor* is an important predator of thrips, mites, and other small soft-bodied prey (Askari and Stern 1972; Salas-Aguilar and Ehler 1977). This and other species of *Orius* are known sources of biological control in orchards (Westigard *et al.* 1968; Niemczyk 1978; McCaffrey and Horsburgh 1986), and our results suggest that mullein could be a source of early spring populations of *O. tristicolor* in orchards. McAtee (1924) collected *Orius insidiosus* (Say) overwintering on common mullein in Maryland.

Predatory mites were abundant in mullein, and included three genera (*Galendromus*, *Typhlodromus*, *Amblyseius*) that are common in apple and pear orchards of North America (McGroarty and Croft 1978; Croft *et al.* 1990; Horton *et al.* 2002), where they provide biological control of pest mites (Hoyt 1969). As with spider mites in orchards, predatory mites may colonize fruit trees from herbaceous or shrubby vegetation within or adjacent to orchards (McGroarty and Croft 1978; Johnson and Croft 1981; Alston 1994). Thus, the present study suggests that common mullein could act as a fairly important source of beneficial mites that provide biological control of pest mites in Pacific Northwest orchards.

There was substantial variation among sites in densities of arthropods overwintering on mullein (range: 272 arthropods per plant to 1986 arthropods per plant). Any of several factors could have contributed to this variation, including host quality, types and amounts of insecticides used in nearby orchards (e.g., Thistlewood *et al.* 1990), and local environmental or microenvironmental conditions. We hypothesized at the beginning of this study that sites close to one another geographically would tend to have taxonomically similar communities compared to sites geographically separated. There was no support for this hypothesis (Fig. 1), possibly due to the fact that two taxa (Thripidae and Phlaeothripidae) were almost invariably the most numerically dominant taxa at all sites, and comprised more than 80% of all arthropods collected.

CONCLUSIONS

Both the leaf rosettes and stalks of common mullein provided overwintering habitat to a large and taxonomically diverse collection of phytophagous and predatory arthropods. Because this plant species commonly occurs in disturbed habitats adjacent to tree fruit orchards in the Pacific Northwest, it may be an important source of both pest and beneficial arthropods colonizing orchards. It is not possible to speculate on whether growers benefit from having large stands of mullein growing near their orchards, as the potential benefits must be judged relative to the possible harm caused by pests which overwinter on the plant or use it as a host during summer. The net effect in an orchard of being adjacent to stands of mullein would depend, at a minimum, on the numbers of pest and beneficial arthropods overwintering in the stand (which appears to be highly variable among stands), as well as each species'

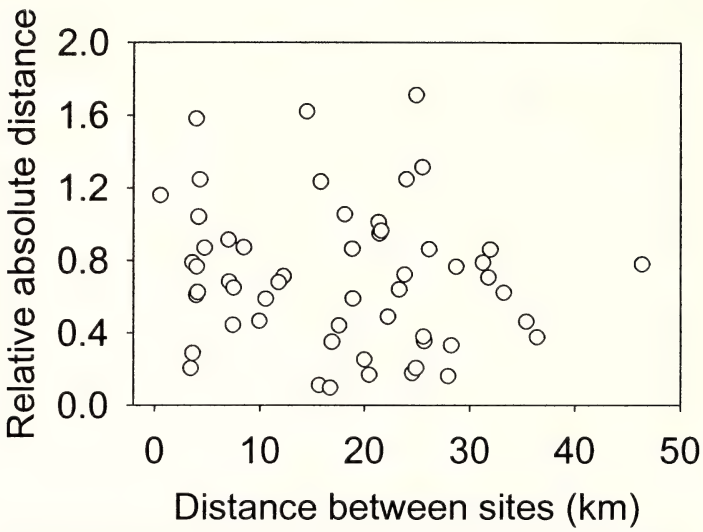

Figure 1. Scatter plot showing relationship of relative absolute distance (i.e., taxonomic similarity) and geographic distance for all possible pairings of sites. Smaller values of relative absolute distance indicate increasing taxonomic similarity between sites. Analysis limited to Insecta at family level.

tendency to disperse into orchards. Until we better understand factors affecting overwintering densities of specific pest and beneficial arthropods, and their post-overwintering movements, it is impossible to predict whether mullein is beneficial or detrimental for growers.

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SCIENTIFIC NOTE

New Aquatic Beetle Records for Canada (Coleoptera: Haliplidae, Dytiscidae)

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ABSTRACT

Three species of aquatic beetle, *Peltodytes simplex* (LeConte) (Haliplidae), *Agabus oblongulus* Fall (Dytiscidae) (both from southern British Columbia) and *Ilybius oblitus* Sharp (Dytiscidae) (from southern Ontario) are confirmed as members of the Canadian fauna based on specimens deposited in the Spencer Entomological Museum at the University of British Columbia.

The most recent checklists for the aquatic beetle fauna of Canada are Larson *et al.* (2000) (Dytiscidae) and "Checklist of Beetles of Canada and Alaska" (Bousquet 1991) (all other families). In order to ensure the accuracy of such lists, it is important that each record be traceable to an accessible voucher specimen whose identity and provenance can be verified (McCorquodale 2001, Wheeler 2003).

The collections in the smaller museums found at universities and other institutions across Canada are a valuable resource for the documentation of Canada's biodiversity (Wiggins *et al.* 1991). These collections are frequently overlooked in taxonomic and biodiversity studies (McCorquodale 2001). In part, this neglect is due to chronic under-funding and under-staffing and the lack of authoritative determinations. We have been reexamining the Hydradephaga in the Spencer Entomological Museum collection (SMDV), checking the determinations and building a database of specimen information. A number of interesting records have been found; three in particular stand out and are reported here.

***Peltodytes simplex* (LeConte)**: BC, Jaffray, 16 Jul 1955, G. Stace-Smith, 1 male (SMDV). *Peltodytes simplex* was previously known from the southwestern United States (California, Nevada) and northwestern Mexico (Baja California) (R.E. Roughley, unpublished). We are unaware of any records for this species from either Washington or Oregon; there are no records for Utah (Kuehnl 2002). There seems little reason to doubt the accuracy of the collection data as G. Stace-Smith was a respected collector who collected prodigiously in British Columbia. This record represents a major northward range expansion for this species and implies a disjunct distribution. Similar disjunct distributions are known in other species, however, it is unclear in this case if the gap in the

distribution is real or an artifact of collecting effort. The current status of *P. simplex* in British Columbia is unknown as there appear to be no subsequent records.

***Agabus oblongulus* Fall**: BC, Metchosin (in "fresh" creek behind beach), 1 Apr 1976, J.D. Reynolds, 1 male (SMDV); BC, Victoria, 13 Feb 1985, B.F. & J.L. Carr, 1 female (CNCI). This species is very similar to *A. punctulatus* Aubé and a number of the latter species labeled as *A. oblongulus* were found in the SMDV and Canadian National Collection of Insects (CNCI). The two species are separated by overall shape and by characters of the male protarsal claws and aedeagi (Larson *et al.* 2000). Unassociated females cannot always be identified with confidence. The *A. oblongulus* specimen in the SMDV is a male and we are confident of its identity; the CNCI specimen is an unassociated female so we cannot be as confident of its determination.

Agabus oblongulus may not be a new addition to the Canadian fauna as Criddle (1929) included it in his summary of new Canadian records for 1928. No voucher specimen for that record is known and because of the difficulties in correctly determining this species, such a record cannot be accepted without a voucher specimen. Its inclusion in Larson and Roughley (1991) is probably based on four specimens in the CNCI collected by H.B. Leech in Salmon Arm. We reexamined those specimens and found that they are *A. punctulatus* not *A. oblongulus*.

***Ilybius oblitus* Sharp**: ON, Rondeau Provincial Park, 26 Jun 1985, G.G.E. Scudder, 1 female (SMDV). *Ilybius oblitus* has a widespread distribution in the eastern United States and its occurrence in Canada was expected (Larson *et al.* 2000). This species is included in Larson and Roughley (1991). As there are no Canadian specimens of this species in the CNCI (Y. Bousquet, personal communication), it is possible that its inclusion was based on the SMDV specimen.

Based on the records reported here, *P. simplex* needs to be added to the "Checklist of Beetles of Canada and Alaska" with an entry under BC. The listings for *I. oblitus* (ON) and *A. oblongulus* (BC) are now validated by voucher specimens. Larson *et al.* (2000) needs to be amended as follows: *I. oblitus* (225a) needs to be added to Table 1 with an entry for ON; the species totals then become 277 for Canada and 160 for ON. The distribution information in the species discussions needs to be updated for *A. oblongulus* and *I. oblitus*.

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SCIENTIFIC NOTE

Flight activity of *Agriotes lineatus* L. and *A. obscurus* L. (Coleoptera: Elateridae) in the field.

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The dusky wireworm, *Agriotes obscurus* L., and the lined click beetle, *A. lineatus* L. (Coleoptera: Elateridae) were introduced to British Columbia (BC) from Europe around 1900 (Wilkinson *et al.* 1976). Their initial discoveries in BC (King 1950; King et al. 1952) and the Maritime provinces (Eidt 1953) were of particular importance at that time, since both species were considered among Europe's most destructive insects (Eidt 1953). In recent years, these species have become major pests of small fruit, vegetable, ornamental and forage crops throughout the Fraser Valley of BC (Vernon *et al.* 2001).

Since their discovery in Canada, it has been stated that *A. lineatus* and *A. obscurus* populations do not fly (Eidt 1953; Wilkinson *et al.* 1976), although flight activity in both species has been reported from Europe (Brian 1947). Whether these species actually fly in Canada is of importance, since the efficacy of various alternative control methods under consideration (e.g. mass trapping, mating disruption and physical exclusion) would likely be affected by flight activity. This note describes a number of independent observations made by the authors under field conditions in the lower Fraser Valley of BC in 2001 and 2002, which verify that flight activity occurs in both *A. lineatus* and *A. obscurus.*

Agassiz, 2001: In a 1 ha fallowed field in Agassiz, BC, a Vernon beetle trap (PheroTech Inc., Delta, B.C. V4G 1E9) baited with *A. obscurus* pheromone (Vernon *et al.* 2001) was inspected at 1530 on 22 May, 2001. The temperature at that time was 28 °C under sunny skies with only a slight breeze. The contents of the trap, which consisted of 85 male *A. obscurus,* were emptied into an open metal pan for sorting. Although most of the beetles were dead, a number were still quite active and one beetle climbed onto a film vial in the pan and took flight. It flew about 3 m to the east, then turned and gained altitude from 1 m to 2 m and flew west, at one point flying about 2.5 m high. The beetle flew for about 30 m at which point it was caught in mid air about 2 m above ground and saved for identification. The specimen was confirmed as a male *A. obscurus* (by R. Vernon).

Ladner, 2002: Several click beetles were observed in flight between 1230 and 1530 on 12 May, 2002 in a 1 ha field of pasture surrounded by larger fallow fields in Ladner, BC. The temperature was 24 °C at 1200 under sunny skies with westerly winds at 13 km/h and a relative humidity of 64%. The field directly west of the pasture was in the process of being cultivated, and at least 20 click beetles appeared to be flying toward the pasture from that direction. A number of the click beetles in flight were captured and tentatively identified in the field as a mixture of *A. lineatus* and *A. obscurus.*

When the thick grass of the pasture was also inspected, large numbers of *A. lineatus* and the occasional *A. obscurus* (about 5 to10 beetles/m^2) were observed crawling up the blades of grass, raising their elytra and taking flight. Out of 20 beetles captured in flight by hand, every one was capable of escaping from the captor's open hand via flight. Flights were best described as direct and deliberate with little to no side-to-side movements. Beetles gained altitudes up to 4 m with the majority flying between 1 and 2 m in height. The beetles appeared to be relatively strong fliers, travelling at the speed of a

brisk jog or approximately 5 to10 km/h. Distance covered while flying ranged from less than 1 m to 100 m on one occasion, with an average flight covering a distance of 2 to 3 m. Twelve beetles were intercepted mid-flight on clothing while traversing the pasture. The captured specimens were confirmed (by R. Vernon) as *A. lineatus* males (6) and females (2) and *A. obscurus* males (4).

Flight behaviour was again observed in the field of pasture between 1430 and 1700 on 24 May, 2002. Temperatures ranged from 16-17 °C during this period under scattered cloud with westerly winds at 7 km/h and relative humidity between 56% and 46%. Flight activity was not as prevalent as on 12 May, with only eight beetles being observed in flight. Most flights appeared to occur in random directions within the pasture, with no beetles being observed to enter into or exit from the surrounding fallow fields. Six beetles were captured in flight and positively identified (by R. Vernon) as male *A. lineatus* (5) and male *A. obscurus* (1).

Surrey, 2002: Both male and female *A. obscurus* and *A. lineatus* were observed in flight between 1300 and 1700 on 12 May, 2002 at a suburban residence in South Surrey, British Columbia. The flight activity coincided with the first warm day of the beetle emergence period (R.S. Vernon, unpublished data), at a temperature of approximately 26 °C under sunny skies. Beetles were observed climbing blades of grass on a recently cut lawn. Successful flight from the grass usually took several attempts and short flights in the range of 10 cm were common. With longer flights, beetles rose at a constant velocity up and out of the yard at altitudes of 1 to 4 m. A single male *A. lineatus* successfully took off from the lawn, gained an altitude of about 1 m, descended towards a deciduous shrub and circled a horizontal branch before landing on the upper side. Closer inspection revealed the presence of an *A. lineatus* female 5 cm away. At 1600, an average density of four click beetles/0.09 m^2 of lawn was recorded. Active beetles were found in the house all that day, but had not been seen the previous day. By around 1700, flight activity had mostly ceased. Beetles were searched for daily throughout the rest of the summer, but were never observed in a mass flight again. Of 20 beetles captured in flight, 6 male and 5 female *A. lineatus* and 4 male and 5 female *A. obscurus* were positively identified in the lab (R. Vernon). Females frozen and dissected later were found to contain eggs in good condition.

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